U. S. DEPARTMENT OF AGRICULTURE,

WEATHER BUREAU.

BULLETIN No. 5.

OBSERVATIONS AND EXPERIMENTS

ON THE

FLUCTUATIONS IN THE LEVEL AND RATE OF MOVEMENT

OF

GROUND-WATER

ON THE

WISCONSIN AGRICULTURAL EXPERIMENT STATION FARM

AND AT

WHITEWATER, WISCONSIN.

BY

FRANKLIN H. KING,

Professor of Agricultural Physics, University of Wisconsin;
Physicist, Wisconsin Agricultural Experiment Station.

Published by authority of the Secretary of Agriculture.

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LETTER OF TRANSMITTAL.

U. S. Department of Agriculture,
Weather Bureau,
Washington, D. C., August 15, 1892.

Sir: I have the honor to transmit herewith a report on "Observations and Experiments on the Fluctuations in the Level and Rate of Movement of Ground-Water on the Wisconsin Agricultural Experiment Station Farm and at Whitewater, Wis.," by Prof. F. H. King, of the University of Wisconsin, and to recommend its publication as Weather Bureau Bulletin No. 5. In this connection I would state that this is the third paper of a series on the relations of soils to meteorology, the object of which is to elicit information from specialists, rather than to indicate the views held by the Department on the subjects treated.

Very respectfully,

Mark W. Harrington,
Chief of Weather Bureau.

Hon. J. M. Rusk,
Secretary of Agriculture.

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OBSERVATIONS AND EXPERIMENTS ON THE FLUCTUATIONS IN THE LEVEL AND RATE OF MOVEMENT OF GROUND-WATER ON THE WISCONSIN AGRICULTURAL EXPERIMENT STATION FARM AND AT WHITEWATER, WISCONSIN.

FIRST OBSERVATIONS.

When the writer first became associated with the Wisconsin Agricultural Experiment Station in July, 1888, there existed upon the Station farm a double row of silt wells, twenty-four in number, connected with a system of drains. The ground immediately about these wells was seeded to blue grass, and the level of the ground-water had fallen below the level of the discharge pipes in many of these wells, but water still stood in them at distances varying from four to five feet below the surface of the ground. It occurred to the writer, in August of that year, that these wells might possibly furnish an occasion for ascertaining whether the diurnal variations in the rate of evaporation affected, to a measurable extent, through capillarity or root action, the rate of downward retreat of the ground-water surface. Accordingly a record of the height of the water surface in these wells, at 6 to 7 a. m. and 5 to 6 p. m., was kept during about two weeks, from which it appeared that there was a real diurnal change in the water-level, the water in most cases standing higher in the morning than on either the preceding or succeeding evening. That the water should be found lower on the evening following the morning was naturally anticipated on account of the general lowering of the water-surface by lateral drainage and the supposed possible lowering by upward flow through the capillarity of the soil and the pumping action of roots; but the general decided rise of the water in the majority of the wells during the night did not appear in accord with fluctuations due directly to the causes named. The surrounding topography and the distribution of vegetation over the surface, at the time the observations were being made, chanced to be such as to suggest that possibly the rise at night might be due to the large consumption of water during the daytime which resulted in depressing the level of ground-water in the locality of observation below the natural slope due to drainage, so that the rise during the night was due to hydrostatic pressure and lateral drainage from the surrounding higher lands or from lands where vegetation was, for the time being, making less demands upon the water in the

soil. If this were the true explanation of the large fluctuations observed, it might be expected that those localities where most water was being consumed by vegetation would, other things being similar, show the largest diurnal fluctuations. To test this phase of the question, two other wells were dug, one in a field of growing corn 100 feet to the east of the line of wells in question and the other in a piece of oat stubble the same distance to the westward.

A comparison of the diurnal changes in the water-level of these wells proved that the fluctuations were unequal, being largest in the center of the corn, smallest in the oat stubble, where the least evaporation was to be expected, and intermediate in amount on the margin of the cornfield under the blue grass, which had been cut and was now short. The measured fluctuations, as they occurred in the three wells, are shown graphically in Fig. 1 for six consecutive days, beginning on the morning of September 8, 1888.

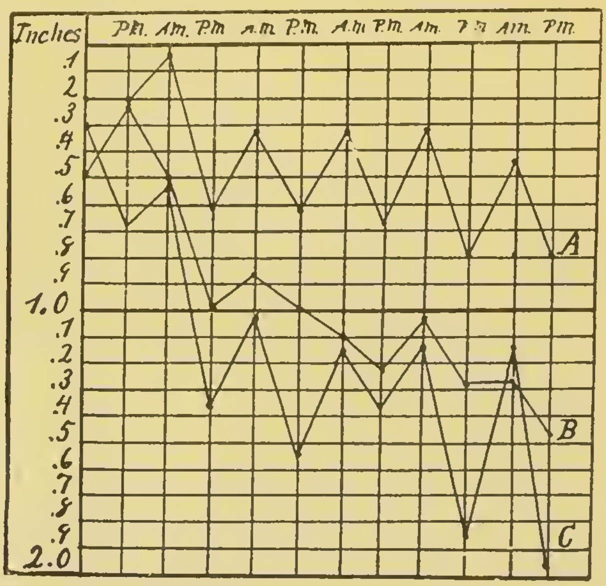

FIG. 1. Diurnal fluctuations in wells; *A*, on margin of cornfield; *B*, on oat stubble; *C*, in corn.

While these observations appeared to favor the view that the diurnal fluctuation of the water-level in these wells might be largely, if not wholly, due to a relatively rapid withdrawal of water from the soil by root action during the day, the fact that the water rose in the wells during the night to a height nearly equal to that which it had occupied on the morning of the previous day could not readily be accounted for by supposing that the water surface was warped downward by capillary and root action, because the magnitude of the diurnal changes demanded what would appear to be a much larger consumption of water during the day than the mean rate of lowering of the water-level appeared to warrant.

The observations which had been made up to this time showed conclusively that the fluctuations of the ground-water level were really very complex in their character and probably in their origin. It also appeared to the writer that if a ready and accurate means of keeping a record of the fluctuations of the level of standing water in the soil could be devised, new light might be thrown upon the percolation of rain water into soils of different types which lysimeters, from their necessarily limited areas and artificial character, cannot be expected to give. It was hoped also that such observations might be made to throw some light upon the distances below the surface different kinds of vegetation were able to utilize standing water in the ground.

In view of these and other considerations it was decided to dig a number of these wells in localities where the distance from the surface to standing water, the topography, the character of soil, and kinds of vegetation vary. Twenty-one wells were dug which, together with the 25 silt wells already in existence, made 46 in an area about 1,200 feet by 1,000 feet square. The wells varied in depth from 5 feet to 26 feet, and were made by boring with a 7-inch post auger provided with an extension handle. The wells were tubed with 5-inch drainage tile, surmounted, at the surface of the ground, with one length of 8-inch glazed sewer pipe provided with a galvanized iron cover controlled by lock and key.

INSTRUMENT FOR MEASURING CHANGES IN LEVEL OF WATER IN WELLS.

The instrument used in measuring the changes in the level of ground-water which we shall first consider is represented in Fig. 2, and consists of a chain with numbered links of uniform length, carrying, at its lower end, a heavy poise and provided with a micrometer at the other, graduated to read thousandths of an inch; this is mounted upon a base which can be placed upon the top of the well and attached to any desired link in the chain.

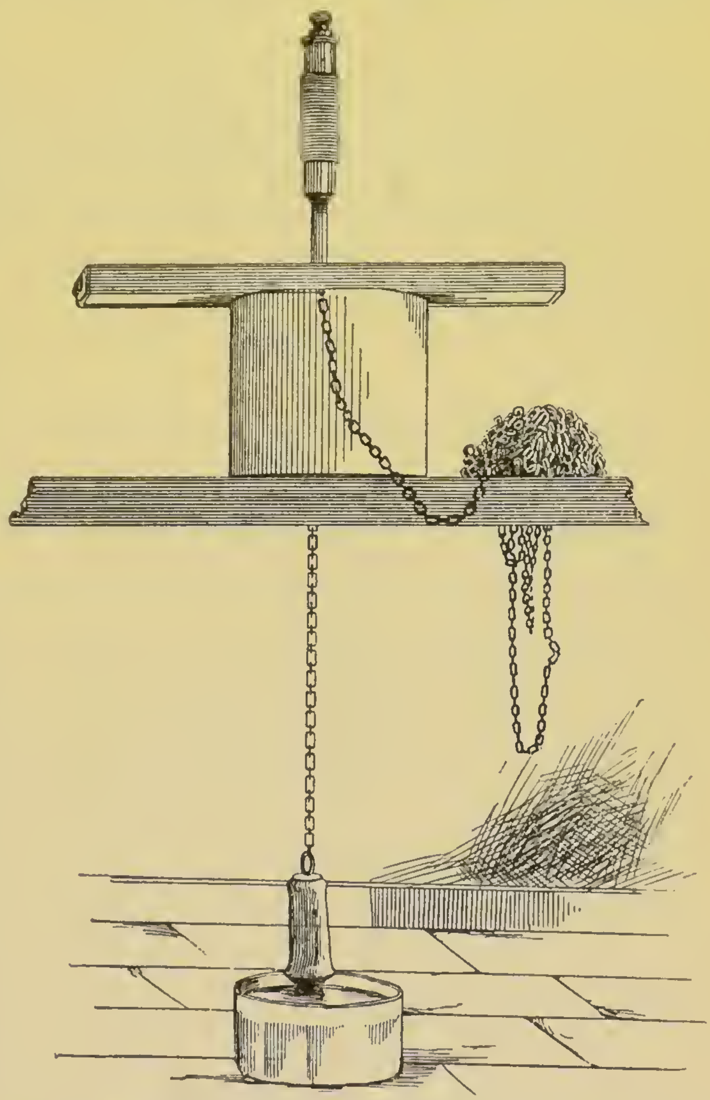

FIG. 2. Micrometer and chain for measuring changes in the level of water in wells.

The essential part of the poise is a hemispherical button of glass one inch in diameter which makes the contacts with the water surface. By lowering the poise gradually, until the button comes in contact with the water, surface tension, by drawing the water up on the button, develops waves on the water which, by their reflection of light, enable the moment of contact to be readily noted even in 6-inch wells 30 feet deep. Neither a plane nor a conical surface of contact develops such strong waves as does the hemispherical form.

The micrometer consists of a central spindle provided with a hook upon which the chain may be hung. This spindle is moved up or down by a hollow screw which slides over a core graduated to tenths of an inch, and the face of the screw is divided into 100 divisions, which enables distances of one-thousandths of an inch to be read off. With this instrument it has been found possible to measure with certainty changes of level in the water less than .03 of an inch.

TOPOGRAPHY OF THE AREA OCCUPIED BY THE WELLS.

The contour map, Fig. 3, will convey some idea of the differences of relief as they exist in the area under consideration. The hill shown in the center of the east side of the contour map rises to the eastward and attains a height of 111 feet above the lake, and then drops down to near the level of Lake Mendota about one mile to the eastward. To the southwest of the map the surface continues to rise nearly 80 feet higher and constitutes a long ridge lying parallel with the one above. The second hill, shown on the east margin of the map, is a small knoll not extending farther beyond the boundary of the area mapped than it does into it.

The exact position of all wells within the area under consideration is shown upon the contour map, where they are designated by numbers.

GEOLOGICAL STRUCTURE OF THE LOCALITY.

The experiment station farm, upon which the wells are located, lies just within the terminal moraine of the second glacial epoch, and the glacial till is laid down upon the very unevenly eroded surface of the Madison sandstone. All of the wells of series *A*, *B*, *C*, and *D* lie wholly in the till; wells 48, 49, 50, 51, and 53 pass through the till and penetrate the rock a few feet, while well 52 is said not to have reached rock at a depth of 84 feet, or 36 feet below lake level. Rock was reached in well 53, 16 feet below the lake, and 13 feet in well 48, but in wells 51 and 50 rock was reached 6 feet and 8 feet above the lake level, respectively.

The till is quite heterogeneous in its character, but is much more even at the level of ground-water than above. The whole area is mantled with a stratum of 2.5 feet to 4 feet of reddish clay containing pebbles and bowlders irregularly and generally sparsely distributed through it, the pebbles and bowlders being coarser and more numerous on the higher grounds. Beneath this mantle there is generally a rather rapid transition to a sand usually quite uniform and free from gravel everywhere below the 9-foot contour. Beneath the surface of higher levels the transition is into a coarse sandy and gravelly till containing stone 3 to 8 inches in diameter in considerable numbers but usually, before water is reached, the coarse materials are greatly decreased or

entirely disappear and water is found in a sand of varying degrees of coarseness, it being, as a rule, decidedly finer than that under the lower grounds. Under the higher lands the sand below often approaches quicksand in fineness.

CONFIGURATION OF THE SURFACE OF THE GROUND-WATER.

The surface at which standing water is found in the ground is very far from being horizontal, as an inspection of Fig. 4 will show, where the contours are drawn to show the surface of standing water, as observed on June 20, 1892, at the 54 wells included in the area.

It will be observed, in the first place, that the level at which water stands in the wells is everywhere decidedly above the level of water in Lake Mendota, to which the contours are referred. Even in well 29, only 150 feet from the lake shore, the water on that date was found standing 7.2 feet above the lake level. In the well at Agricultural Hall, situated about 3,600 feet east of well 52 on the same ridge, but where the surface of the ground is 88 feet above the lake, the water in the ground stands 52 feet above the level of the lake, and this well is all the way in the till and not over 1,200 feet in a direct line from the shore and not much farther from land near lake level both to the southward and eastward.

A second point to be noted here is the general tendency of the water to stand at the highest level under the highest ground, but there are notable exceptions to this, and more at the particular date which the map represents than has been true at former times. Well 52, located upon the highest ground within the area, has yet the lowest recorded water-level excepting those within and near the tile-drained section shown in the map. This well, however, is a deep one encased in 84 feet of 6-inch iron tubing which is screw-coupled so as to be water-tight except at the bottom. Besides, it was in use during the whole winter, nearly all the water it could supply being taken from it until April 1. After the middle of April it was thrown entirely out of use and so continued until past the middle of May. At the time the measurement was taken the well was in use, but only a few pails of water were taken from it daily. Numbers 53 and 48 are also tubed wells, 52 and 40 feet deep respectively, but were not in use when the levels were taken. All other wells are comparable when account is taken of the fact that the drains, which were still discharging when the levels were taken, would tend to carry the ground-water to an abnormally low level in their immediate vicinity.

The real and marked exception to the general rule of the tendency of the ground-water to present a surface approaching conformability with that of the land above is found in well 39, where the water is 16.5 feet above the level of the lake, while that in well 38, less than 60 feet distant, is only half that amount.

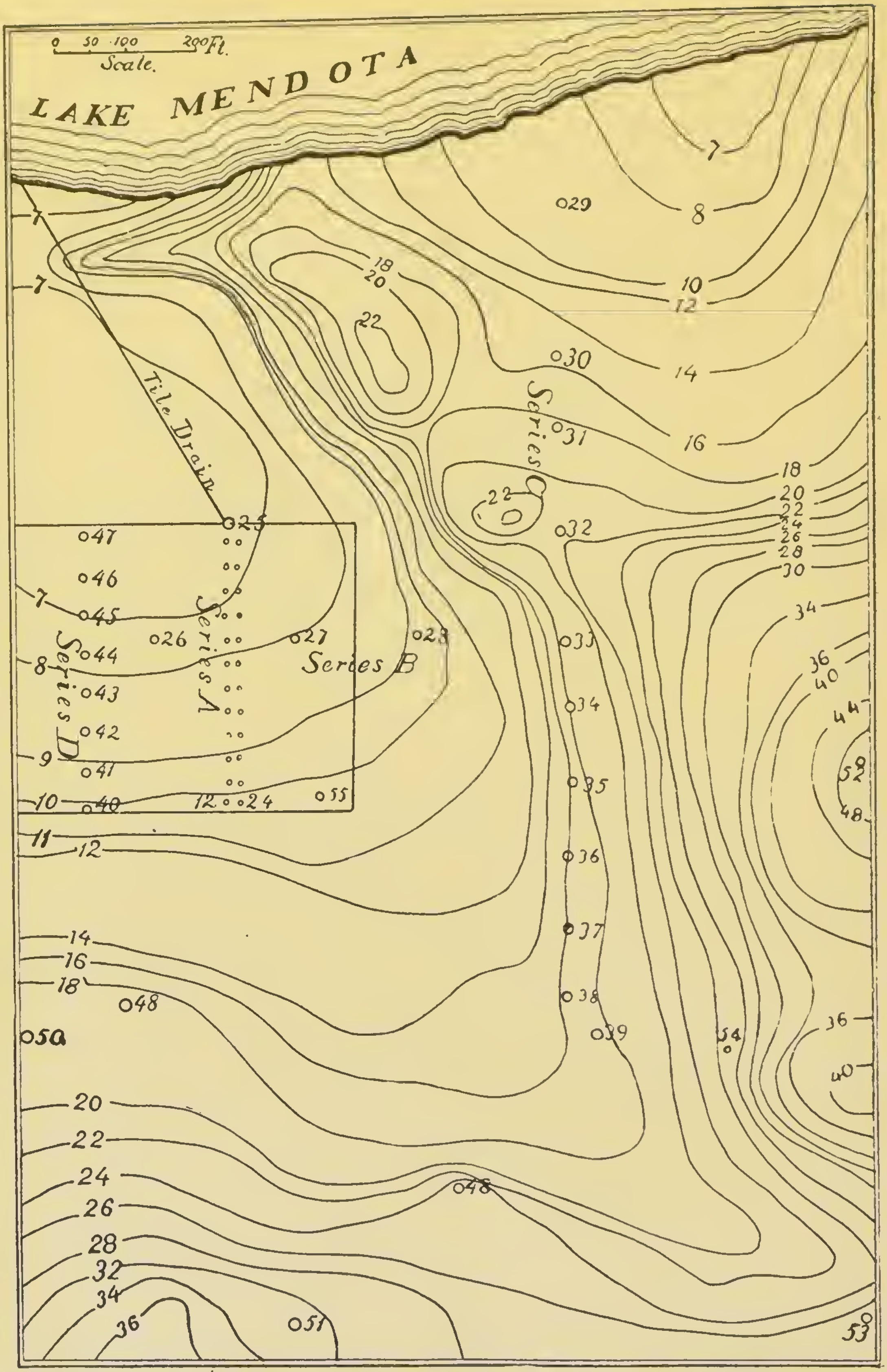

FIG. 3. Contour map of area occupied by wells. Figures in lines give height of contours above lake in feet; other figures indicate numbers of wells.

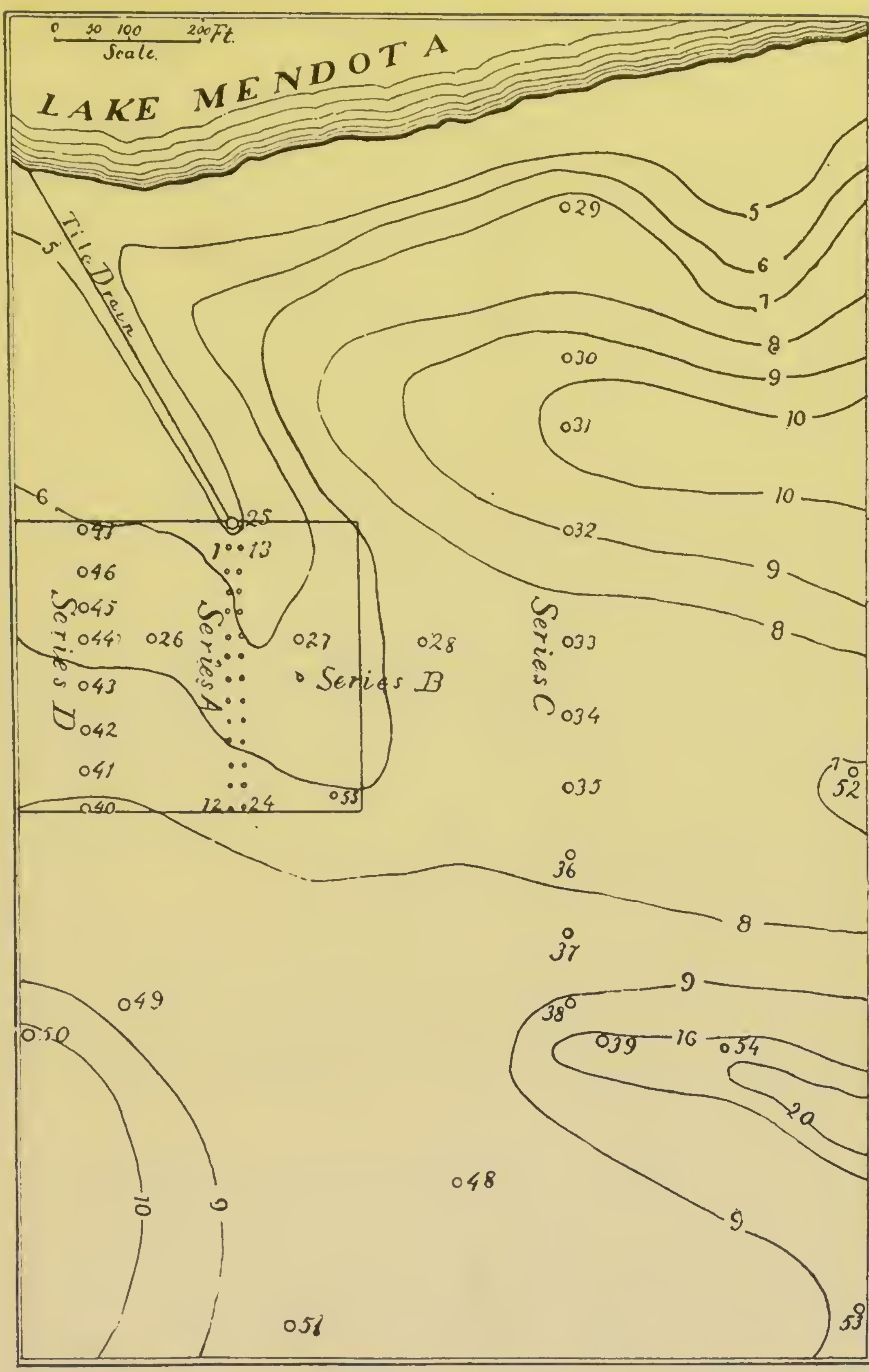

FIG. 4. Contour map of ground-water surface on June 20, 1892. Figures in lines give height of contours above lake in feet; other figures indicate numbers of wells.

The rise of the ground-water surface as it recedes from natural drainage outlets, and the resulting tendency to develop a surface unconformable with a true water-level, is not a local peculiarity, as has been pointed out by Baldwin Latham*, who expresses the fact as follows:

"The greatest elevation of the subterranean water is usually found under the highest lands, and the least elevation under the lands having the lowest levels. The flow of water laterally is from the hills to the valleys and longitudinally down the valley lines; therefore, as a general rule, the flow of subterranean water conforms to the surface of the country."

THE PERCOLATION OF WATER INTO WELLS.

The measured height of water in a well is not always a true index of the level of ground-water in that vicinity. If the well is in use and considerable quantities of water are being taken from it, the well becomes a drainage outlet toward which the water flows just as soon as the level of the water in it is depressed below that of the general level. The longer such a well is used, when percolation through the soil above does not equal the demand, the more the water-level is depressed below the normal and the wider the area of depressed water-level becomes. This causes the water which supplies the well to flow toward it down a continually decreasing slope, and at the same time through soil passageways of ever-increasing length and resistance. Under these conditions, it is evident that a well which is sunk but a few feet below the general level of ground-water would suffer a rapid decrease of capacity during dry seasons, whereas one which is sunk 15 to 20 feet below the natural water-level in the soil would make up in steepness of gradient for the increasing distance from which the water must move toward it from the surrounding soil, as an inspection of Fig. 5 will show.

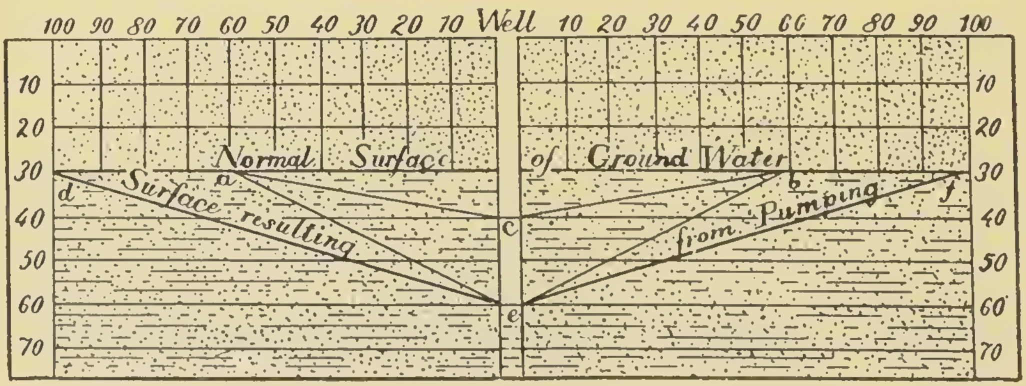

Fig. 5. Effect of pumping on the ground-water surface.

When the water in the well is lowered to 40 feet below the surface, as shown in the figure, and the water surface becomes depressed so

* Report of British Association in 1877, page 207.

as to conform with the line *a b c*, there is a head or gradient of 1 in 6 tending to force the water into the well, but when the water is lowered to *c*, 30 feet below the general water-level, the gradient becomes 1 foot in 2; but even after long pumping, and the water-level becomes depressed so as to conform with the line *d e f*, the gradient is still steeper than in the first case, being 1 foot in 3 nearly.

It is evident, therefore, that in providing wells for farm stock there should be an ample depth below the normal level of standing water in the ground, and this must vary with the character of the soil or rock in which the water is stored and through which it must flow to enter the well, the depth required increasing, generally, with the degree of fineness of soil or rock because the resistance to flow increases with the smallness of the particles.

There are times when the height of water in wells is above that of the general level of ground-water in their immediate vicinity, and this occurs during wet seasons after protracted heavy rains and is more marked in clayey soils than in those more open, and more marked in shallow than in deep wells. In the percolation of rain water there is a general tendency for the water to flow laterally towards and accumulate in the wells. This effect is shown very clearly in Fig. 7, which represents the changes in the level of the water in wells, series *C*, whose positions are designated in the two contour maps, Figs. 3 and 4, pages 16 and 17.

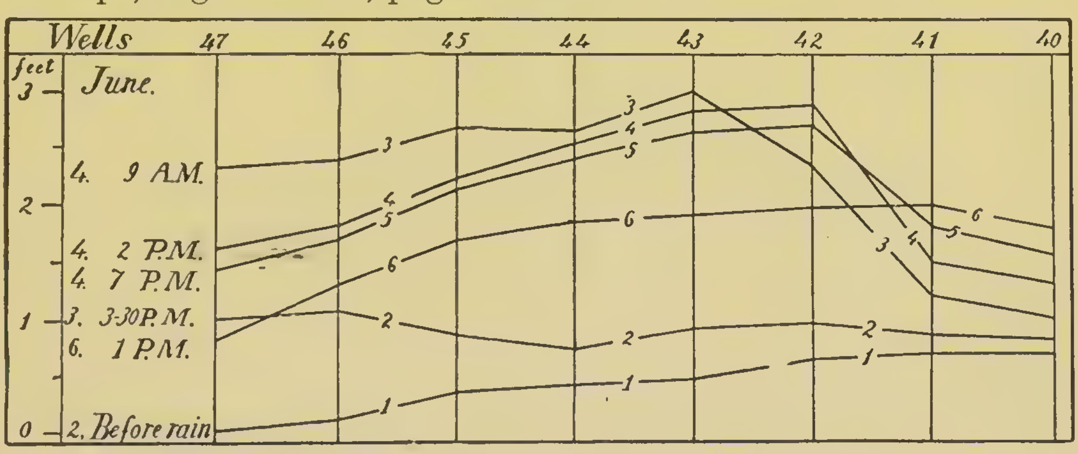

FIG. 6. Changes in the level of water in wells due to percolation.

These changes occurred after a rainfall of 3.19 inches, distributed in time as follows: June 2, 7.30 a. m. to 9 p. m., 1.38 inch; June 3, 7 a. m. to 2 p. m., .41 inch; 9 p. m., July 3, to 7 a. m., July 4, 1.18 inch; 9.15 p. m., July 4, and again 6.30 a. m., July 5, .22 inch.

It will be seen that a rainfall of 3.19 inches produced a rise of water in well 43 of about 2.5 feet, while in well 40 the rise did not exceed 1 foot. The greatest height of water in well 43 was reached on the morning of June 4, while the water in well 47 was still rising slightly 52 hours later, when the water in all the other wells had fallen from .9 foot in well 43 to 1.5 foot in well 47. It is true that the surface of the ground at well 40 is 3.3 feet higher than the surface at well 47,

but the chief difference in the amount and rate of rise in the two wells is not due to this fact, neither is it due to water entering the wells at the immediate top, as will be seen from Fig. 7 and the observations stated in connection with it.

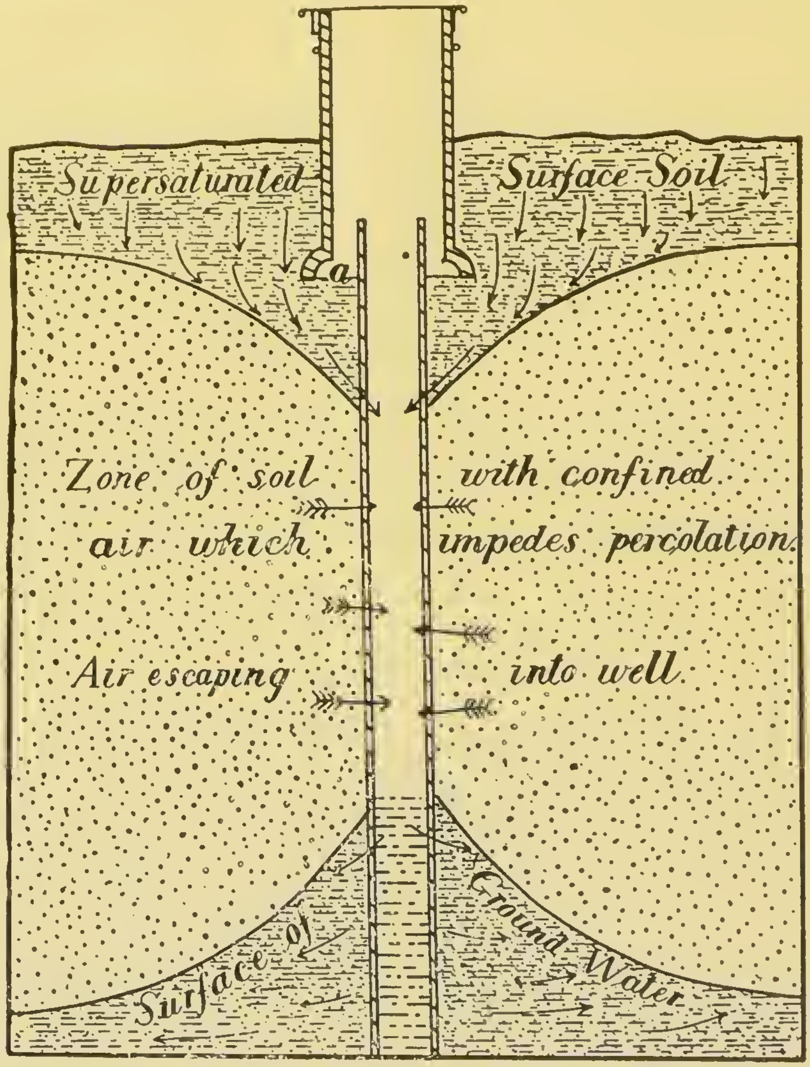

FIG. 7. Percolation of water into and out of wells.

All of the special wells used in these investigations are protected at the surface of the ground with a section of glazed tile provided with a lid, as shown in section in the cut, and it was repeatedly observed during times of rapid and excessive rises of water in the wells due to percolation that the surface of the soil at (*a*) remained dry during the whole interval of percolation, showing conclusively that the water did not enter the wells through the soil at the immediate surface.

The rise of water in wells above the general drainage surface during times of heavy rains is due to the inability of the soil-air to escape readily upward through the supersaturated surface, for so long as it can not escape it prevents the water from entering the soil spaces occupied by it; wells, however, which are not curbed with impervious tubing furnish an easy avenue of escape for the air, and it is forced out into the wells, allowing the water to follow it, so that there comes to be established, during times of percolation, a movement of water

and air in the soil about a well something as represented by the arrows in Fig. 7.

In the sandy and more open soils, where the interspaces near the surface do not readily become closed with fine sediment moved by the water, there is not as great a lateral flow of water toward the wells, and the water does not rise in them very much more than the general water-level in the ground is raised during such times, and it is because the soil about wells 47 and 46 is much more sandy and open than it is about the others of this series that there is less rise of water in them at such times. That the lesser rate of rise and amount of it in wells 47 and 46 can not be due to the greater depth of soil through which the water is forced to penetrate is proven by the fact that while in well 28, where the distance from the surface to water at the time was very nearly the same as in well 47, the interval of time before percolation into it became evident was shorter and the amount of rise in it greater even than in well 40.

In trying to fill soil with water, in cylinders a foot in diameter, I have found it practically impossible to do so by adding water to the top, on account of the great difficulty of escape of air laterally or upward. In such cases it has been necessary to introduce the water through the bottom or else to put the soil into the water.

That fine textured soils do become almost impervious to air under moderate changes of pressure when they are saturated with water, even in the field under perfectly normal conditions, I have proven repeatedly with a piece of apparatus represented in Fig. 8.

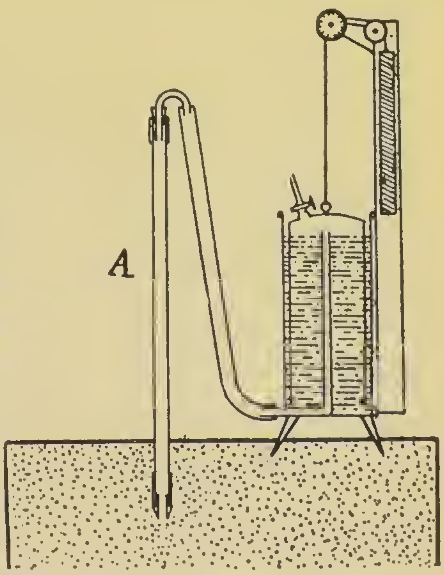

Fig. 8. Soil aspirator for studying the permeability of soil to air.

In using this apparatus the soil tube, *A*, was forced into the ground to near the desired depth at which the permeability to air was to be tested and then removed and the core of soil turned out. The tube was then returned to its place, and with an auger which would reach a fixed distance below the top of the soil tube, the hole was deepened; then by attaching the aspirator as shown in the figure a definite suction was established and the rate at which the air could be drawn through the soil into the aspirator determined. In this way it was shown that all the surface soils on the station farm are nearly impervious to air immediately after heavy rains and that all the clayey subsoils are completely so when they are nearly or quite saturated with water. These experiments, however, have not been performed under a greater reduction of pressure than one-tenth of an inch.

Referring now to the contour map of the surface of ground-water it will be observed that well 39, while on rather low ground, has the water standing in it at an abnormally high level, and this is due to the excessive percolation into the well during the present wet season. On the other hand, well 52, which is in the highest ground and yet with a very low water-level, represents the other phase which we have considered, a case where the ground-water has been lowered by excessive pumping.

A SANITARY PROBLEM.

There is a sanitary aspect of this question which should not be overlooked. Well 39 showed, by the rapid fall of a little more than 2 feet which took place in it during less than 10 days following the measurement recorded on the map, that its great height of water was due to lateral percolation into it, and the point to which I wish to direct attention is that we have here a ready means of ascertaining whether a well is subject to surface contamination or not. A sudden large rise and fall of the water-level in a well, associated with heavy rains, can have no other interpretation than that water reaches the well without being filtered through a very large amount of soil. An abrupt rise and fall of a few inches might have no significance here, as will be seen from observations recorded in another place, but where there is a rise and fall of a foot or more there can be no doubt but the well is liable to yield, at times, unsanitary water if the surface surroundings are such as to permit of it. The observations here recorded also indicate that wells located in clayey soils and subsoils may be much more subject to such surface contaminations than others in more open and porous ones.

Just how far it is practicable to protect wells which are subject to contamination in this manner, by using iron tubing or other similarly impervious curbing, is a matter which merits careful investigation, for it is a vital question in the building of country homes. It is generally taken for granted that wells thus constructed are safe against the infiltration of surface water, and it may be true to a large extent; but it does not appear improbable, in pumping water from a well tubed up with iron, that the rapid withdrawal of water from about the immediate terminus of the tubing would tend quite as strongly to bring the new supply of water directly downward from above as to induce it to come from below or from lateral directions, and if this is true, it is evident that the surface surroundings of a well used for domestic purposes should be scrupulously cared for even when provided with impervious curbing.

ONE CAUSE OF DECREASE OF HEAD IN ARTESIAN WELLS AND AT PUMPING STATIONS.

It is not an uncommon occurrence for artesian wells to show a

decrease of head, which, in many cases, is very appreciable and not apparently caused by seasonal fluctuations of the level of ground-water, and the same fact has been observed at pumping stations also. In my judgment, the observations made in the preceding section offer a partial explanation of these changes; for the opening of an artesian well in an impervious soil through which water has not been discharging must have the effect of depressing the surface of the ground-water which contributes to the well, and as the new drainage surface of equilibrium must occupy a lower level it follows that the head must suffer a permanent decrease, and this might be such as to cause certain wells in a locality to cease flowing altogether.

SEASONAL CHANGES IN THE HEIGHT OF GROUND-WATER.

The impounding influence of all porous lands lying above drainage levels, causes the ground-water surface to rise during wet seasons while during dry ones it falls so that the effective head in artesian wells and in springs is increased or decreased periodically in accord with the fluctuations of the yearly rainfall and those other conditions which tend to diminish the amount of water which is able to enter the land. In the same manner, also, the capacity of ordinary wells to supply water varies as the general level of the ground-water rises and falls. The locality under consideration here is one in which the supply to shallow wells must be almost, if not quite, the percolation water of purely local rains.

The wells in series *C*, which are in the higher land of the station farm and most remote from the system of the drains, are best suited to show the long period fluctuations due to the quantitative relationship existing between the amount of rainfall and the rates of drainage and percolation. When the wells were sunk, in August, 1888, there was water in all of them except 31 and 36, and the level of the water in them is shown in Fig. 9, on a stated date in 1888, 1889, 1890, and 1892. During the latter part of the summers of 1889 to 1891, inclusive, all of the wells of this series became dry, except No. 30, which is nearest to the lake, and in each case it has been true that, after going dry, they did not contain water again until after April 1, the following spring.

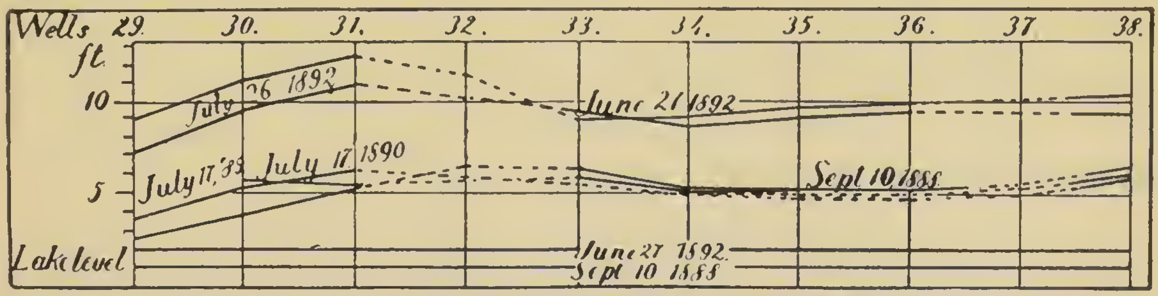

FIG. 9. Profiles of ground-water surface along the wells of series *C*.

It will be seen that the surface of ground-water in June, 1892, is from 4 to 5 feet higher than at any other season since the records began.

The level of Lake Mendota was also higher, but its range has been confined between this level and one almost two feet below.

RELATION BETWEEN THE AMOUNT OF RISE IN THE SURFACE OF GROUND-WATER AND THE RAINFALL.

When, in the spring of 1892, the surface of ground-water first began to rise above the level of the bottoms of the wells in series *C*, its contour had approached very close to horizontality, as shown in Fig. 10, where the profile lines of May 7 and May 21 show the configuration of the surface at those times. Between May 21 and June 7 the arithmetical mean rise for all of the measured wells was 1.5 foot, and the rainfall between those dates was 4.02 inches. Between June 7 and June 27 the mean rise was 2.38 feet, and the rainfall associated with it 4.97 inches. The total mean rise between May 21 and June 27 was 3.88 feet, and the rainfall for the same period 9.05 inches. During the first of these periods the water rose .373 foot for each inch of rain; in the second it rose .479 foot, and during the last, .428 foot for the same amount of rain.

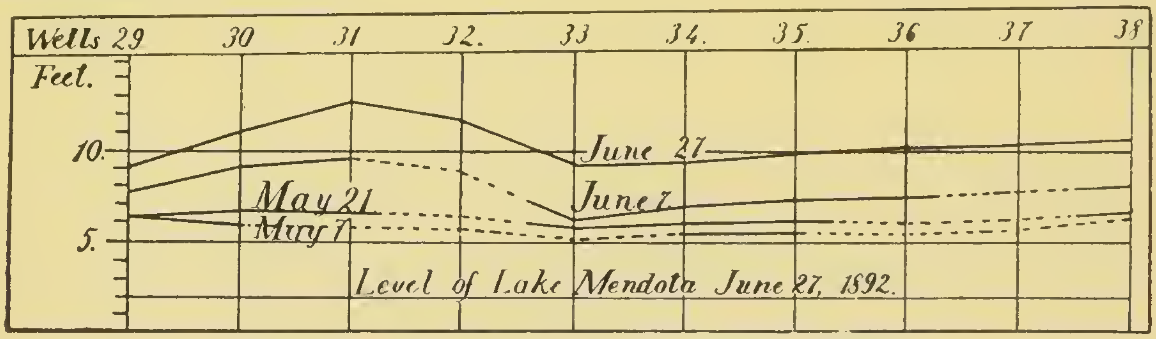

Fig. 10. Rise of the ground-water in relation to rainfall.

If we now refer to Fig. 6 and take the mean distance between the two lines 1 and 6 as representing the true rise of the ground-water surface due to percolation, we shall have for a rainfall of 3.19 inches a rise of 1.27 foot, or at the rate of .398 foot for each inch of rain. The general mean of all these is about .42 foot of rise in the ground-water for each inch of rain.

Determinations made at this station show that there is about .4 cubic foot of space in one cubic foot of dry sand, and that capillarily saturated sand standing one foot above water, such as the rise here considered took place in, would contain about 18 per cent. of its dry weight of water, while the weight of one cubic foot of such water-free soil is not far from 105 pounds. Under these quantitative relations the capillary water should occupy .32 cubic foot and the unoccupied space into which water could percolate would be only

$$1 \text{ cubic foot} - (.6 + .32) = .08 \text{ cubic foot},$$

or 138.24 cubic inches. Under these conditions an inch of rain should fill a cubic foot of soil more than full; but as the ground-water was raised at the mean rate of only about .42 foot it follows that either the soil did not contain 18 per cent. of its dry weight of water at the time

the rains occurred or else that there was, during the time, a large amount of percolation through the zone under consideration.

THE CAPILLARY STORAGE CAPACITY OF LONG COLUMNS OF SOIL.

There is in my own mind no doubt that the soils considered in the last section, into which the water percolated, did not contain 18 per cent. of water at the time under consideration, and my reasons for this conviction are these: In coarse, sandy soils at least, if not in all others, the capillary holding power decreases in some undetermined ratio with the length of the column above standing water, as I have proven by the following experiment: Columns of medium grained plastering sand 42 inches long were constructed and suspended in a vertical position, as represented in Fig. 11. The sand for this experiment was stirred in water to expel all adhering air and then poured into the tubes through a funnel, sand and water together, the tubes being frequently shaken and jarred to insure a solid packing of the sand.

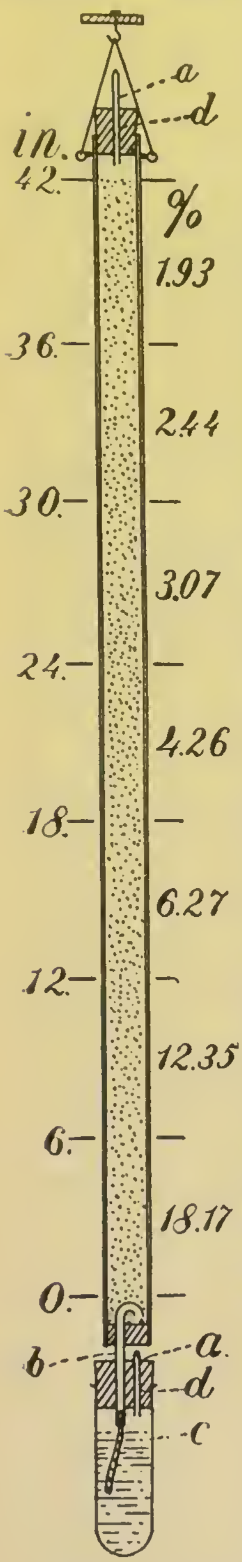

Fig. 11. Method of determining the distribution of capillary water in long columns of soil.

The tubes were hung in place on April 26, 1892, and percolation had not ceased on May 14, although the rate had become very small. At this time 20 cubic centimeters more water were poured into the tubes at the top, when a rapid percolation was set up immediately, but did not cease entirely until some time between June 3 and 10. On June 10 percolation had ceased, as shown by the receptacles having lost in weight .0237 grams to .0036 grams. The tubes were then cut into 6-inch sections, and the water content of the sand determined by placing the sections directly in the dry-oven. The tube which had been wet with distilled water possessed the distribution of capillary water indicated in Fig. 11, where it will be seen that there is a decreasing amount as the distance above standing water increases, it being 18.17 per cent. in the lower 6 inches and only 1.93 per cent. in the upper, with a mean of only 6.927 per cent. This difference in distribution was due wholly to percolation, as the nearly constant weight of the whole apparatus proved, that only showing an almost inappreciable loss through evaporation of water from the fine vents in the two corks at top and bottom.

It was to me surprising that the percolation was so large and yet toward the close so extremely slow, but results of similar import have been obtained through direct observations upon soils in their natural

positions in the field. In the Seventh Annual Report of this Station, page 144, a record is given of the change in the water content of the upper 5 feet of soil situated about 70 feet northwest of well 52, Fig. 3, which, during the interval from October 28, 1889, to April 14, 1890, was covered so as to exclude snow and rain, the object being to ascertain whether, during the winter, there was an increase of water in the soil through the aid of capillarity in drawing water up from below. It is there shown that instead of becoming more moist during the winter the water content actually decreased, and to the extent of 1.66 per cent. of the dry weight of the soil in the upper 4.5 feet; the lower 6 inches alone showing a gain in moisture. This loss of moisture referred to I then attributed to surface evaporation, "and possibly to lateral and downward translocation." Other observations now at hand, but which need not be detailed here, convince me that the chief loss of moisture in this soil during the winter was due to slow percolation downward, and that soils are drained more and more by percolation downward as the surface of ground-water recedes. Judging from the per cent. of water retained by the plastering sand it would appear that the zone of soil through which the ground-water rose during the interval from May 21 to June 27 may not, at the beginning, have contained more than 6 per cent. of the dry weight of the soil of water, and that it is due to this fact rather than to underground drainage that the surface of standing water in the ground was not carried to a greater height than was observed.

RELATION OF THE NORMAL GRADIENT OF THE GROUND-WATER SURFACE TO TILE DRAINAGE.

The prime function of tile drainage is to hold the surface of ground-water at an adequate depth so that there shall be ample room for root development, and as the ground-water rises with each increment of distance from the drainage outlet the proper distance to place the tile apart in a given soil, where they are to be placed at a stated depth, turns upon the resistance which the soil offers to the flow of water through it, for it is this resistance, just as in the flow of water through pipes, which determines, primarily, the steepness of the ground-water surface.

To determine the actual contour of the ground-water surface in a tile drained field when the drains were doing duty, a line of seven wells was sunk midway between the lines of tile which are laid in the area designated on the contour map, Fig. 3. The lines of tile in this field are laid as nearly as may be 33 feet apart and at a distance below the surface of the ground of about 4 feet. The wells referred to were put down midway between the lines of tile, and therefore were situated 16.5 feet from the drains on either side and at a distance not exceeding 30 feet from the line of silt wells into which the drains discharge.

The soil of this locality consists of 6 to 8 inches of medium clay loam followed by 2.5 to 3 feet of clay, below which is a stratum of rather coarse sand, in the upper surface of which the tiles are usually laid, and in spots this sand contains some gravel. The tiles are 3 inches inside diameter and laid on a grade of about 2 inches in 100 feet. At the time the levels were taken the tiles were discharging less than one-twentieth of their capacity.

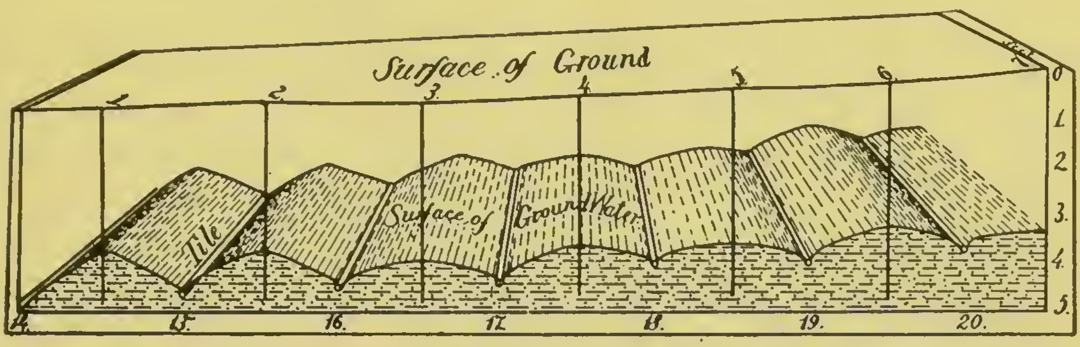

FIG. 12. Surface of ground-water between tile drains 48 hours after a rainfall of .87 inch.

The observed contour of ground-water in this field at 8 a. m., May 13, 48 hours after a rainfall of .87 inch, is represented in Fig. 12. The highest water-level in any well between these lines of tile on this date, when referred to the tops of the tile between which the wells are, was one foot in the case of well 1, above tile 14, and the least was about .3 foot in the case of well 5 above tile 18. Both wells 5 and 3 were sunk into a sand containing a considerable amount of gravel, and to this fact is probably due the less steep gradient at these places. Between well 2 and tile 16 two other wells were sunk, one two feet from the drain and the other midway between the drain and well 2. In the well 2 feet back from the drain water stood .3 foot above the top of the tile, and in the other, .45 foot above; the profile would present, therefore, a more or less curved contour, convex upward.

Assuming the water-level at the several lines of tile to be flush with the tops of the tile and regarding the water surface as presenting a right-line section, the mean gradient for the ground-water surface would be one foot in 25.38 feet. In well 29, 150 feet from the lake shore, the water stood 7.214 feet above the level of the lake on June 27, 1892, and this would give a gradient of one foot in 20.79. In the case of the well at Agricultural Hall to which I have referred as having a water-level 52 feet above the lake, and situated about 1,250 feet from the shore, the mean gradient would be one foot in 24.4. In the fall of 1888, September 10, when the water-level in the wells could not have been affected by lateral percolation into it, the gradient between well 29 and the lake was 1 foot in 35.86 feet.

In the tile drained area under consideration the configuration of the water surface did not remain as shown in Fig. 12, but changed as the water was carried away by the drains, and in Fig. 13 is shown the profile of the ground-water on these different dates. The changes

which had occurred in the level of the water show that it was not drawn down at a uniform rate at all places, the surface falling fastest under the highest ground, where the water-level was also highest; also that the hydrostatic pressure of the water was there effective, tending to produce a horizontal movement from the upper toward lower portions of the tile drained area, associated with a downward vertical movement under the higher area, increasing the rate at which the level fell in that place and apparently decreasing it in the lower section by determining an upward tendency of the water from below.

It is a constant feature in the discharge of water from this system of drains that those tiles laid in the lower ground continue to carry away water months after those under the higher ground have ceased to do so, and as there is no more soil to hold water for the drains to carry away under the low than under the higher ground it follows that there is a tendency for the water to rise up into the zone affected by the lower tiles.

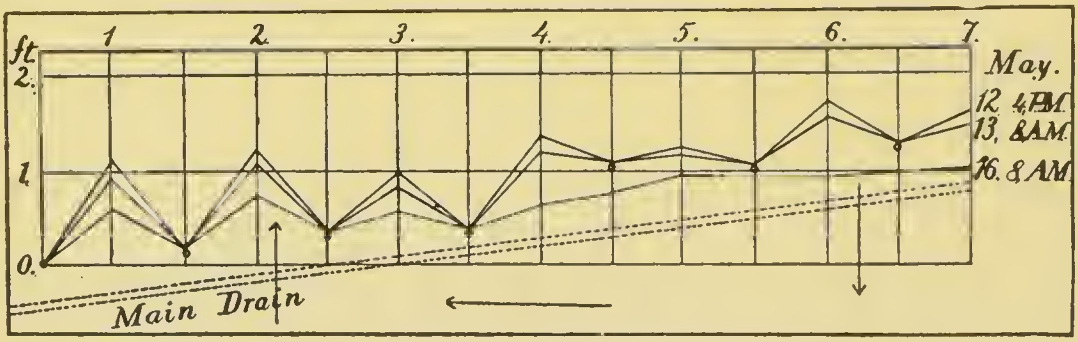

FIG. 13. Changes in level of water between tile drains.

NATURAL SUBIRRIGATION.

It is a fact long established by practical experience that many low lands which require tile draining in order to bring them under cultivation, and lying adjacent to higher areas, become, when so treated, if adequately done, the most productive lands of the locality, and while there are several conditions which render them so the paramount one is the water supply naturally provided by the upward tendency of it under the lower lands, coming from the supply of impounded water in the soil of the surrounding higher ground in the manner illustrated by the observed changes in the conformation of the groundwater surface referred to in the last section. The tile drains when properly placed serve during seasons of superabundance of water to hold the water-level below the zone of root action, while during seasons of deficient rainfall they do not interfere with its rise by hydrostatic pressure into the region where it becomes available to the growing crops. This is an important principle to understand in the selection of land for intensive farming.

Not all low lands adjacent to high areas are subject, in equal degree, to the natural subirrigation referred to, for geological differences of

structure necessarily modify the movement of the rain which has entered the ground or may even prevent it from entering it so as to become available in the manner under consideration. The geological structure best adapted to the storing of water in the high lands and of giving it out gradually to the lower areas adjacent, is represented in Fig. 14, where the surface is mantled to a depth of 3 to 4 feet with clay soil and subsoil; this mantle on the high land passes by degrees through a porous, sandy and gravelly clay into a sand and gravel or pure sand of considerable depths into which the surface waters readily penetrate, and out of which they flow laterally with comparative ease. Under the hillside this coarse gravel and open storage material shades into a medium grained or rather fine sand through which the water can flow with some degree of freedom but not so rapidly as to fail to store the water to a considerable height above the surface of the low land. This type of geological structure is that possessed by the tract of land under special consideration here, and is very common throughout wide areas of the United States which are heavily mantled with the deposits of the later glacial epoch. The terminal moraines of this country are impounding reservoirs of great extent and capacity into which the rain sinks immediately and is there stored under conditions of least possible loss by evaporation, to be given out gradually in restricted but innumerable areas. Heavy rains which in differently constituted sections are lost to agriculture in disastrous floods are here safely and economically stored. It is to this stored water escaping slowly from the ground again, more than to direct rainfall and flat topography, that we owe the existence of our innumerable small lakes and the many acres of swamp and of lowland pastures so characteristic of glaciated areas, and it is to these many naturally subirrigated tracts which I wish to call attention, as being so promising for the purposes of market gardening and other types of intensive farming.

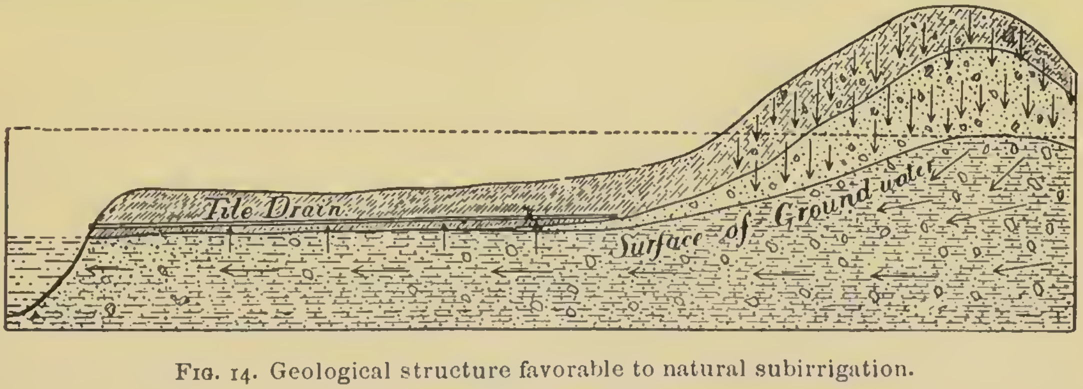

Fig. 14. Geological structure favorable to natural subirrigation.

There is another point in this connection to which attention should be called. There are numerous tracts of country underlaid by artesian waters, at varying depths, and where it is only necessary to penetrate the overlying impervious strata to obtain water at the surface. Now, it is a well established fact that the very best Portland cements are very far from being wholly impervious to water even under moderate pres-

sures, and in view of this fact it has often occurred to me that a careful study of the yield of crops per acre for years of deficient rainfall, in artesian districts as compared with that of adjacent areas which are not, might reveal the fact that there is a not inconsiderable supply of water from below; which might help to explain the peculiar productiveness of certain sections.

This question is not without significance in its bearing upon the supply of water to cities, through the instrumentality of artesian wells, because if it is true that there is a slow but general drainage of artesian basins upward through the confining strata, one effect of this drainage might well be to develop an increasing porosity of the confining beds which would diminish the effective heads of the wells and might, in time, even cause them to cease to flow altogether, not from a diminished rainfall, but by a diversion to agricultural uses through a general subirrigation of the waters which had been or are being used for city purposes.

It does not appear impossible either, that in districts not underlaid by artesian waters, there might be a general lowering of the water in the wells of the higher grounds on account of an increasing porosity of the soils of the surrounding lower lands.

FLOW OF GROUND-WATER FROM THE LOWER UNDER THE HIGHER LANDS.

When a series of dry years have occurred, like the three just past, the surface of ground-water is drawn down to an abnormally low level, as was the case on May 7, shown in Fig. 10. Then when such a period is followed by heavy rains the soils of the low lands frequently become filled first so that the normal configuration of the water-surface is reversed, that under the low lands not infrequently standing higher than that under the higher areas. The reasons for this reversal are two, first, the low lands have less storage capacity than the high on account of there being less depth of soil, and second, not all the rains which fall upon the high lands can remain upon the surface long enough to enter the soil, and, as a result, the low lands not only receive practically the same amount of rainfall but a portion of that which falls upon the hills is carried, by surface drainage, down upon them, and in this manner the ground-water level may be carried several feet above that under adjacent higher lands. Referring to Figs. 9 and 10, and to the two contour maps, Figs. 3 and 4, it will be seen that in September, 1888, the water-level at well 33 is higher than at any other point, whereas on June 27, 1892, the water there has a lower level than at any other point along that line of wells. Under these conditions there is a reversal of the direction of the underground movement of the soil water, the current setting from the low areas toward the higher lands, and by this reversal there is restored to the high lands a portion of the water which fell upon

them as rain after it had flowed down upon and percolated into the bordering lower grounds. Well 33 has been, and is at this date, July 18, still rising, while the water in the other wells is falling.

THE RATE AT WHICH THE LEVEL OF THE GROUND-WATER SURFACE CHANGES.

The mean rate at which the ground-water surface rises and falls has varied between rather wide limits, but, as a general rule, a much shorter period has been required to produce a given rise than has been consumed in producing an equal change downward.

In Plate I, I have plotted the twice-daily observations on wells of Series *B* and *D*, extending over 100 days beginning June 8, 1889, and ending September 17. At the beginning of these observations the surface of the ground-water was already below the level of most of the tiles so that the lowering of the surface could not be influenced directly by the action of the drains. The total mean fall of the ground-water surface for wells 40 to 46 and 27 and 28 was 13.95 inches during the 80 days from June 18 to September 6, or a mean daily rate of .174 inch. During 131 days, from May 27 to October 29, the total mean fall was 20.495 inches, with a mean daily rate of .156 inch for wells 40 to 46. During 112 days, from June 9 to October 7, 1890, the total mean fall for the same wells was 20.086 inches, or a mean daily rate of .179 inch.

An inspection of the chart shows that the different wells did not all fall at a uniform rate, and if we arrange them in the order of the distance of standing water in the ground below the surface we shall have—

	Inches.
Well 46 fell during 80 days	13. 2
Well 27 fell during 80 days	12. 1
Well 45 fell during 80 days	12. 9
Well 44 fell during 80 days	13. 25
Well 28 fell during 80 days	13. 3
Well 43 fell during 80 days	13. 8
Well 42 fell during 80 days	15. 0
Well 41 fell during 80 days	15. 4
Well 40 fell during 80 days	16. 6

With but one exception, that of well 45 as compared with 46, the water fell more rapidly in the shallow than in the deep wells. The more rapid fall of the ground-water under the lower land was due to two causes, first, the shorter distance to the drainage outlet at the lake making the resistance to the flow less, and, second, to a more rapid loss of water at the surface of the ground through combined capillary and root action.

To ascertain whether corn exerts a measurable influence in depressing the ground-water surface, the ground occupied by the wells of series *D* was divided transversely into as many plots as there are wells,

and in 1889 corn was planted over wells 40, 42, 44, and 46, while the ground about wells 41, 43, 45, and 47 was left fallow; then in 1890 the conditions were reversed. Determining the mean fall of the water on the fallow plots and comparing this with the mean fall observed on the corn plots for the two years, we get the results given in the table below:

Table showing mean fall of water on corn ground compared with that on the fallow ground.

Date.	Corn.	Fallow.	Difference.
1889.	*Inches.*	*Inches.*	*Inch.*
May 27 to June 20	1·973	1·918	·055
May 27 to July 1	3·516	3·156	·360
May 27 to July 10	5·442	5·091	·351
May 27 to August 1	8·585	8·353	·232
May 27 to August 24	12·088	11·978	·110
May 27 to September 26	15·443	15·324	·119
May 27 to October 29	20·573	20·416	·157
1890.			
June 19 to July 2	2·914	2·646	·268
June 19 to July 10	7·248	6·965	·283
June 19 to August 1	13·532	13·359	·173
June 19 to August 28	17·456	17·052	·404
June 19 to September 27	19·872	19·485	·387
June 19 to October 7	20·288	19·884	·404

It will be here seen that during the whole of the growing season the mean fall of the water under the corn plots was greater than it was under the fallow ones, not simply in 1889, but also in 1890, when the plots were reversed. It would appear, therefore, so far as two concordant trials can prove a complex problem, of this character, that corn does exert a measurable influence in depressing the surface of standing water in the ground where it lies at the distance below the surface which it occupied in these trials, which was 7.77 feet at well 40 in 1889, on September 26, when the corn was cut. During the season of 1890, after the June rains, the water was raised about 1 foot above the level of the preceding year at this date, and this difference was maintained throughout the growing season, and associated with this higher level of the ground-water there was a larger difference between the levels of the water under the fallow plots and those bearing corn, a feature which should be expected if an increase of vertical distance diminishes the rate at which water can be moved toward the surface.

The abrupt rise of the water in all of the wells shown on the left margin of Plate I was due to direct percolation of water following the rainfall of a little more than 1.1 inch shown at the foot of the plate. Examining these rises in detail, it will be seen that the two shallowest wells, Nos. 5 and 41, responded at once, while the others lagged behind varying lengths of time, the highest point not being reached in the deepest wells, Nos. 46, 45, and 28, until after the lapse of 48 to 72 hours after the rain began. It will be noticed, also, that wells 46

and 45, which are in the more sandy soil, show only the general rise of the whole ground-water surface, while all the others show by the abrupt fall of the water that there had been a lateral percolation of water into them.

There are other long period and nearly synchronous rises shown by the curves which are common to all of the wells, but which do not appear to be so plainly the direct result of percolation, although all of them occur near or at the time of rainfalls of greater or less amounts. These are six in number, the last one being double; the first occurs after July 2, following a rainfall of about .5 inch, but is of small magnitude; the second is larger and follows a similar rain which fell on the 14th; the third, a very marked one, following the rains of the 26th to the 29th, but the culminating point is not reached until August 2, where there is another rain of .05 inch, and six days later than the main fall of rain; following August 8, the fourth occurs after a rain of about .5 inch; the fifth is very slight except in well 27, and occurs two days later than a rainfall of .12 inch; while the last and most pronounced rise of all except the one first referred to attains its summit five days after a rainfall of 1.3 inch.

The surface soil had become very dry just before all of these rains, crops were suffering for water badly, and no one of the drains showed signs of discharging, whereas after the first period of rise they did. It does not appear to me, therefore, that these can be cases of rise in the ground-water due to percolation from the surface.

If these are in reality not cases of direct percolation, such fluctuations might be accounted for in this particular locality by supposing that the higher ground, which the map shows to lie between the area under consideration and the lake, retards surface evaporation, as would be the case on other surrounding high lands, while the lower tract, where the wells are located, lying closer to standing water in the ground might permit a more rapid lowering of the water surface by the greater effect of evaporation being added to that of drainage so that the level became here depressed below the level normal to the drainage resistance. If this had really occurred, any cause which would diminish the rate of upward movement of water to the surface from the ground-water surface would permit the level to rise toward the normal drainage level, and thus develop the fluctuations noted. A really serious objection to this view is found in the fact that wetting the surface of soil under certain conditions of dryness induces a more rapid movement of water toward the surface from below, sometimes through depths as great as four feet, as direct observations have shown. There is, however, no evidence presented by the character of the curves under consideration that such an increased movement has developed a more rapid fall of the ground-water as should be true if the influence in question extended to that depth.

But the most remarkable peculiarity presented by these curves is the pronounced, and in some cases extremely large, diurnal fluctuations in the level of water in these wells. The curves show that there is a general tendency for the water either to rise during the night or else to fall less rapidly than during the day, and these will be referred to again.

RELATION OF THE RATE OF FALL IN THE GROUND-WATER SURFACE TO BAROMETRIC PRESSURE.

To ascertain whether there is a difference in the mean rate of fall of the ground-water surface, when judged by well measurements, the data obtained through the use of the micrometer have been tabulated in such a manner as to show the amount of change in the water-level during the interval from highest barometer to the following lowest pressure, which is not less than .1 inch lower, and this has been compared with the change which was found to occur during the following interval of barometric rise to the highest point, which was not less than .1 inch higher.

To render the amounts of change during the different periods comparable, the mean daily rate of change has been determined by dividing the total change observed in each period by the number of days in them. Since rainy periods are associated with times of low barometric pressure, whatever percolation may have occurred during periods of falling barometer would tend to diminish the normal fall of water for times of low pressure, and at the same time tend to increase the fall during periods of high pressure, except at times of large rainfall, which caused the period of percolation to extend into or across one or more periods of high pressure.

Table showing mean daily rate of change in the ground-water level associated with rising and falling barometer.

Period.	Date.	Rainfall.	Changes.			
			Barometer rising.		Barometer falling.	
			Barometer.	Wells.	Wells.	Barometer.
	1888.	*Inches.*	*Inch.*	*Inches.*	*Inches.*	*Inch.*
1	September 18-23	.24	+.59	− .121		
2	September 23-25	.04			+ .116	−.73
3	September 25-29		.74	− .212		
4	September 29-October 1				+ .153	.85
5	October 1-2		.63	− .895		
6	October 2-3		.61	− .441		
7	October 3-4				+ .096	.34
8	October 4-6		.33	− .192		
9	October 9-13				− .045	.27
10	October 13-14		.19	− .233		
11	October 14-16	.13			+ .077	.22
12	October 16-18	.75	.35	− .103		
13	October 18-19				+ .640	.31
14	October 19-21		.52	− .184		
15	October 21-27	.79			+ .046	.60
16	October 27-30		.42	− .129		
17	October 30-31				+ .243	.34
18	October 31-November 1		.10	− .247		
19	November 1-2	.05			+ .307	.19

Table showing mean daily rate of change in the ground-water level—Continued.

Period.	Date.	Rainfall.	Changes.			
			Barometer rising.		Barometer falling.	
			Barometer.	Wells.	Wells.	Barometer.
	1888.	*Inches.*	*Inch.*	*Inches.*	*Inches.*	*Inch.*
20	November 2-3	.41	.31	− .123		
21	November 3-5				+ .043	.22
22	November 5-7	.17	.31	− .130		
23	November 7-10	.58			+ .236	.50
24	November 16-20		.51	− .149		
25	November 20-23				− .045	.28
26	December 3-5				− .078	.44
27	December 5-6		.53	− .240		
28	December 6-7				+ .180	.29
29	December 11-14		.35	− .130		
	1889.					
30	May 3-7				− .103	.60
31	May 7-9	.30	.34	− .274		
32	May 9-10	.15			+ .045	.11
33	May 10-11		.12	− .233		
34	May 11-16	.44			− .062	.23
35	May 16-22	1.01	.34	− .115		
36	May 22-23				+ .045	.23
37	May 23-25	.09	.22	− .210		
38	May 25-27	1.02			+ .398	.38
39	May 27-30		.39	− .245		
40	May 30-June 3	.04			− .016	.33
41	June 3-6		.16	− .182		
42	June 6-7	.07			+ .001	.29
43	June 7-10	.58	.45	− .037		
44	June 10-15				− .153	.07
45	June 15-19	1.14			+ .211	.37
46	June 19-24	.10	.68	− .296		
47	June 24-26				− .149	.31
48	July 3-6	.23	.33	− .173		
49	July 6-9				− .305	.25
50	July 9-11		.16	− .233		
51	July 11-12				− .353	.24
52	July 12-16	.49	.28	− .072		
53	July 16-18				− .148	.43
54	July 18-24		.37	− .214		
55	July 24-28	.83			− .080	.38
56	July 28-31	.29	.48	− .036		
57	July 31-August 1				− .084	.22
58	August 1-6	.05	.30	− .165		
59	August 6-8				− .199	.28
60	August 8-11	.50	.20	− .017		
61	August 11-13				− .139	.30
62	August 13-17	.05	.24	− .129		
63	August 17-20				− .220	.28
64	August 20-26	.12	.34	− .197		
65	August 26-28				− .216	.12
66	August 28-31		.17	− .242		
67	August 31-September 4	.03			− .169	.47
68	September 4-11	1.44	.43	+ .204		
69	September 11-14				− .102	.31
70	September 14-16	.23	.25	− .114		
71	September 18-20				− .074	.48
72	September 20-22		.44	− .184		
73	September 22-23				− .060	.25
74	September 23-27	.09	.47	− .101		
75	September 27-30	.14			− .040	.53
76	September 30-October 2		.39	− .142		
77	October 2-3				− .126	.18
78	October 3-4		.37	− .215		
79	October 4-5				− .099	.24
80	October 12-14		.56	− .104		
81	October 14-19				− .030	.60
82	October 19-23		.58	− .060		
83	October 23-25				+ .106	.80
84	October 25-29		.48	− .070		
85	October 29-November 2	.31			+ .097	.62
86	November 2-5	.03	.95	− .147		
87	November 5-13	.07			+ .110	.67
	1890.					
88	June 2-5	2.97			+7.162	.32
89	June 5-9	.22	.51	−2.931		
90	June 14-16	1.76	.23	+5.340		
*96	June 19-21	.83			+2.105	.24
97	June 21-23	.38	.13	+ .138		

*Some periods in the original tables are omitted here.

Table showing mean daily rate of change in the ground-water level—Continued.

Period.	Date.	Rainfall.	Changes.			
			Barometer rising.		Barometer falling.	
			Barometer.	Wells.	Wells.	Barometer.
	1890.	*Inches.*	*Inch.*	*Inches.*	*Inches.*	*Inch.*
98	June 23–24				— .932	.10
99	June 24–26	.48	.12	— .302		
100	June 26–July 1	.025			— .724	.24
101	July 1–5	.11	.31	— .545		
102	July 5–7	.11			— .289	.24
103	July 7–10		.36	— .549		
104	July 10–14				— .196	.39
105	July 14–16	.10	.41	— .354		
106	July 16–17				— .216	.26
107	July 17–19	.09	.24	— .407		
108	July 21–24	.475			— .201	.45
109	August 1–3				— .284	.14
110	August 3–6	1.505	.21	— .106		
111	August 6–8				— .122	.39
112	August 8–11		.46	— .332		
113	August 11–13				— .046	.21
114	August 13–15		.17	— .361		
115	August 15–16	.15			+ .004	.15
116	August 16–18	.96	.19	— .065		
117	August 18–19	.10			+ .055	.23
118	August 19–20		.15	— .207		
119	August 20–21	.05			— .001	.23
120	August 21–23	.06	.40	— .338		
121	August 23–26	1.35			+ .218	.52
122	August 26–30	.06	.32	— .235		
	1891.					
123	April 8–10				+2.456	.54
124	April 10–12		.41	+1.270		
125	April 12–14	.18			— .127	.31
126	April 14–16	.30	.42	+ .593		
127	April 16–18				+ .328	.32
128	April 18–20		.24	— .505		
129	April 20–23	.52			+1.013	.30
130	April 23–24		.17	— .681		
131	April 27–28	.23	.30	— .990		

If we compare the changes in water-level which occurred during the two long intervals in 1888, when there was no rain, and the long one in 1889 at times of rising and falling barometer we shall have, for the mean daily change, the following results:

	Rising barometer.	Falling barometer.
	Inch.	*Inch.*
Periods 3 to 10	— .395	+ .068
Periods 24 to 29	— .173	+ .019
Periods 76 to 84	— .118	— .037
General mean	— .229	+ .017

For these intervals of time, therefore, there was a mean daily fall of the water-surface during the days of rising barometer amounting to .229 inch, while during the periods of falling barometer there was a mean daily rise of .017 inch.

If we determine the mean daily change during all the periods of rising barometer in 1888 and in 1889, and in those of 1890, after the heavy rains preceding July 5, and compare these with that which

occurred during the periods of falling barometer for the same intervals of time, we shall have the results given below:

Mean daily change for—	Rising barometer.	Falling barometer.
	Inch.	*Inch.*
1888	— .235	+ .141
1889	— .143	— .046
1890	— .295	— .098
General mean	— .224	— .001

These observations show that a generalized curve representing the fall of water in a well would have a form such that the steeper slopes span intervals of rising barometer and the less steep ones periods of falling barometer.

RATE OF CHANGE IN THE GROUND-WATER LEVEL FROM MORNING TO EVENING AND FROM EVENING TO MORNING.

As has already been pointed out, there is a general tendency for the water-level of the wells under consideration to fall more rapidly during the day than during the night, and it is proposed, in the following tables, to give some of the data upon which the above statement is founded. The observations for the several wells have been grouped into periods and the total change which occurred from morning to evening and again from evening to morning for each of these periods determined. To reduce these all to a common unit, the observed total change for each well during a given period has been treated as follows:

Let a = total observed change in well during a given period;
b = length of time, in hours, between the a. m. and p. m., or p. m. and a. m. observations;
n = number of observations in the period.

Then, $\frac{a}{b\,n} \cdot 1{,}000$ = change for 1,000 hours.

This is supposing the observed mean rate to have continued during 1,000 hours. The following table contains the results of this treatment for the wells there specified by Arabic numerals at the left during the periods numbered in Roman at the top:

Table showing changes in the level of ground-water from morning to evening and from evening to morning, computed for 1,000 *hours.*

Number of well.	Period I.		Period II.		Period III.		Period IV.		Period V.	
	A.M. to P.M.	P.M. to A.M.	A.M. to P.M.	P.M. to A.M.	A.M. to P.M.	P.M. to A.M.	A.M. to P.M.	P.M. to A.M.	A.M. to P.M.	P.M. to A.M.
26	−12.632	− 1.128	− 8.259	− 5.266	+3.158	− 2.228	+1.749	+ 2.517	−6.551	+2.586
27	−14.211	+ 1.505	+ .486	−11.285	+2.915	− 5.517	− .486	+ 1.379	−2.936	−2.351
28	− 2.297	− 8.270	+ 1.943	−13.166	+7.288	−10.000	+3.887	− 1.379	−2.232	−2.351
5	....	....	−12.105	+ 4.966	−4.060	+ 2.228	+ .194	+ .552	−8.808	+5.408
13	− 9.473	+ 3.009	− 6.073	+ 1.316	− .486	− 1.379	−1.263	− 1.931	....	....
14	−12.634	+ .460	....	....	....	....	....	....	....	....
15	− 9.473	+ .753	− 5.830	.000	− .541	+ .700	+1.069	− 1.103	....	....
16	−10.526	+ 3.762	− 3.887	− 1.505	−2.707	+ 2.228	− .094	+ .759	....	....
17	−15.789	+ 5.642	....	....	....	....	....	....	....	....
6	−25.263	+ 8.276	−15.304	+ .564	−4.060	+ 1.910	−3.401	+ 3.793	....	....
7	−28.431	+11.285	....	....	....	....	....	....	....	....
39	−41.474	+12.260	− 5.831	−28.589	+8.745	+ 6.207	+2.818	+12.483	....	....
Average	−16.655	+ 3.390	− 6.096	− 5.885	+1.594	− .750	+ .519	+ 1.897	−5.132	+8.23

Number of well.	Period VI.		Period VII.		Period VIII.		Period IX.	
	A.M. to P.M.	P.M. to A.M.	A.M. to P.M.	P.M. to A.M.	A.M. to P.M.	P.M. to A.M.	A.M. to P.M.	P.M. to A.M.
26	−11.539	+ 9.962	−15.351	− 1.069	−11.348	− 9.665	− 8.862	− .271
27	− .970	− 1.097	−10.526	− 4.774	− 3.691	−13.163	− 5.215	− 4.655
28	− 1.144	− 1.628	− 5.012	−10.688	− 3.445	−10.757	− 4.373	− 7.857
5	−10.086	+10.934	−15.915	+ 3.527	−21.821	− 4.634	−91.452	+86.593
40	− 4.541	− 1.593	− 7.205	− 8.194	− 2.969	−10.834	− 5.028	− 7.090
41	− 2.725	− 2.442	− 8.145	− 6.769	− 6.582	− 7.278	− 5.879	− 5.459
42	− 2.859	− .177	−11.842	− 7.909	− 7.737	− 8.047	− 6.966	− 4.660
43	− 6.123	+ 4.317	−10.714	− 4.916	− 7.605	− 7.085	− 6.203	− 5.714
44	− 5.753	+ 5.698	−10.464	− 8.767	− 5.777	−10.951	− 9.719	− 2.179
45	+ .437	+ 1.840	−11.779	−10.118	− 7.574	−10.015	− 7.192	− 4.877
46	−20.600	+24.738	−12.218	−11.044	−12.955	− 5.166	− 9.491	− 1.656
Average	− 5.992	+ 4.596	−10.834	− 6.429	− 8.319	− 8.872	−14.580	+ 3.834

Number of well.	Period X.		Period XI.		Period XII.		Period XIII.	
	A.M. to P.M.	P.M. to A.M.	A.M. to P.M.	P.M. to A.M.	A.M. to P.M.	P.M. to A.M.	A.M. to P.M.	P.M. to A.M.
26	− 8.847	− 1.985	−11.544	− 8.371	+ .027	− 2.643	− 7.042	−11.893
27	− 6.254	− 4.300	− 5.660	− 1.326	− 1.327	− .078	− 8.622	−10.402
28	− 5.967	− 3.026	− 9.403	− 7.791	+ .073	− 2.771	−12.422	− 8.161
5	−11.492	− .936	−13.670	− 6.121	....	....	....	....
40	− 4.385	− 6.769	− 5.206	− 9.709	− 3.273	− 1.964	− 5.867	− 9.357
41	− 6.748	− 5.278	− 8.763	− 7.918	− 1.427	− 2.805	−10.133	− 7.866
42	−12.575	+ .088	−28.963	+12.212	− .864	− 1.800	−10.655	− 7.286
43	− 6.422	− 4.954	−24.451	+10.271	− 3.527	− .550	....	....
44	−11.071	− .495	−16.763	− 1.496	− 3.318	− 2.393	−11.600	− 8.303
45	−35.485	+23.615	−50.897	+29.202	− 1.036	− 8.790	−10.167	− 3.509
46	−11.087	− 3.128	−31.844	+ 9.795	+ 1.336	− .571	−13.222	− 6.661
47	....	....	....	....	+ 1.973	− 1.628	−11.244	−11.232
Average	−10.939	− .652	−18.831	+ 1.704	− 1.033	− 1.644	− 9.179	− 8.467

This table shows that in the majority of cases the rate of fall in the ground-water level is more rapid during the hours from 6 a. m. to 6 p. m. than it is from 6 p. m. to 6 a. m. Now, while there are numerous exceptions to this statement, yet the exceptions are largely confined either to certain wells or else to particular periods, as the following condensed tabulation will show:

	Agreements.	Exceptions.
In well 26 during 13 periods there were	10	3
In well 27 during 13 periods there were	8	5
In well 28 during 13 periods there were	3	10
In well 5 during 10 periods there were	10	0
In well 13 during 4 periods there were	2	2
In well 14 during 1 period there was	1	0
In well 15 during 4 periods there were	3	1
In well 16 during 4 periods there were	4	0
In well 17 during 1 period there was	1	0
In well 6 during 4 periods there were	4	0
In well 7 during 1 period there was	1	0
In well 39 during 4 periods there were	2	2
In well 40 during 8 periods there were	2	6
In well 41 during 8 periods there were	6	2
In well 42 during 8 periods there were	6	2
In well 43 during 7 periods there were	7	0
In well 44 during 8 periods there were	7	1
In well 45 during 8 periods there were	7	1
In well 46 during 8 periods there were	7	1
In well 47 during 2 periods there was	1	1
Making in 129	92	37

There are thus shown to be 71 per cent. of the cases where the mean fall during the daytime is greater than it is during the night. Then, again, of the 37 exceptions, 21 are found in 3 wells and 10 are found in one. If we make the tabulation by periods the case will stand as below:

1888.	Agreements.	Exceptions.
September 18 to 29, Period I, of 11 wells there were	10	1
October 1 to 14, Period II, of 9 wells there were	6	3
October 15 to 28, Period III, of 9 wells there were	4	5
October 29 to November 10, Period IV, of 9 wells there were	6	3
1889.		
May 19 to June 1, Period V, of 4 wells there were	3	1
June 4 to 18, Period VI, of 11 wells there were	9	2
June 20 to 27, Period VII, of 11 wells there were	9	2
July 3 to 17, Period VIII, of 11 wells there were	4	7
July 18 to August 1, Period IX, of 11 wells there were	9	2
August 2 to 16, Period X, of 11 wells there were	10	1
August 17 to 31, Period XI, of 11 wells there were	10	1
1891.		
January 19 to 31, Period XII, of 11 wells there were	5	6
February 14 to 22, Period XIII, of 10 wells there were	7	3

Making in all 129 cases, with 92 agreements and 37 exceptions.

Here, again, 18 of the exceptions occur in periods III, VIII, and XII.

Determining the average change of all of the wells during all of the periods, it is found to be —8.583 inches in 1,000 day hours, and —1.309 per 1,000 night hours. Making a similar determination for periods VI to XIII, inclusive, when the largest number of wells were

being measured at the same time, we get —9.972 inches as the change during the day, and —1.917 as the change during the night for each 1,000 hours.

AUTOMATIC RECORDS OF THE FLUCTUATIONS IN THE LEVEL OF GROUND-WATER.

It became evident very soon, in the study of the changes which take place in the level of ground-water, that not only continuous but synchronous records would be required before the real character and extent of these movements could be made known, and early in the summer of 1891 the practicability of obtaining continuous records was established by mounting a pen upon an axis so that a float, resting upon the surface of the water in a well, would cause the pen to record the movements of the water upon a sheet carried by the drum of a thermograph, and Fig. 15 is a reproduction of one of the earliest rec-

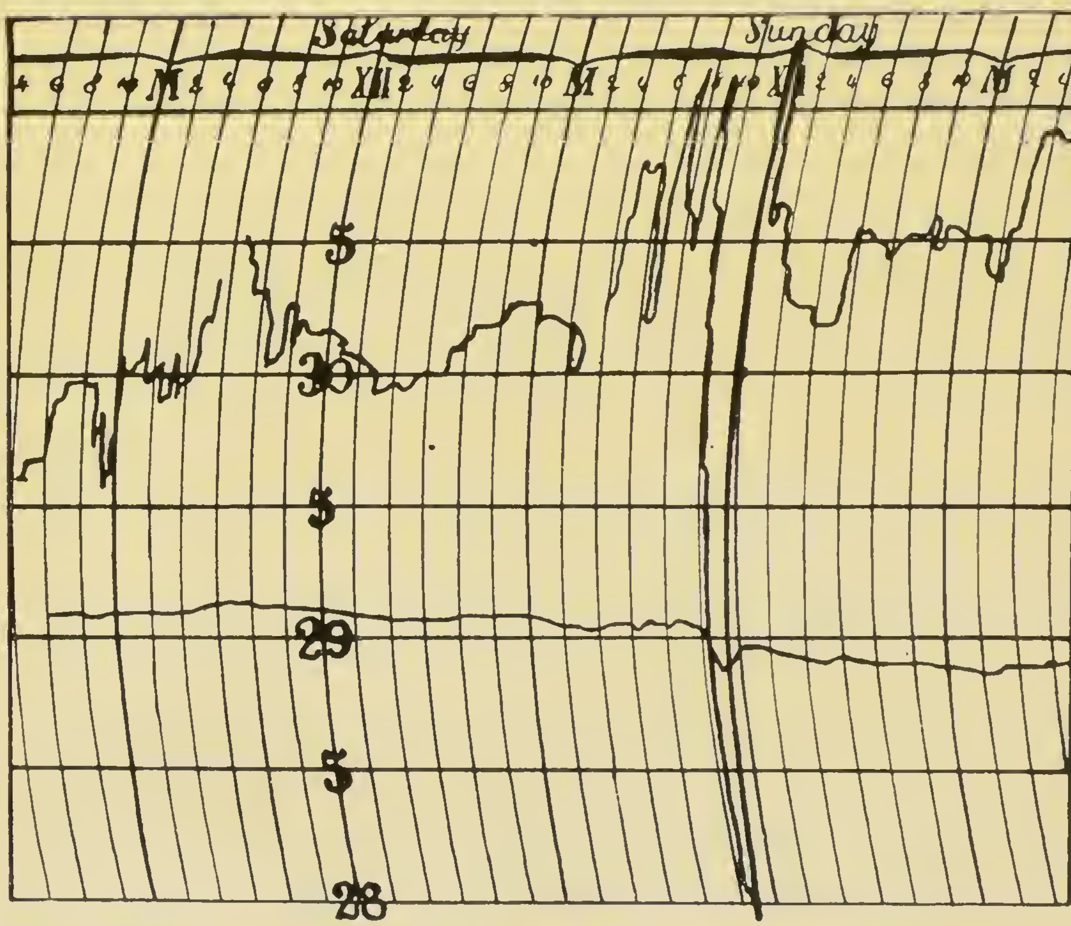

FIG. 15. Automatic record of fluctuations of water in well 48, from 6 p. m., May 30, to 6 a. m., June 1, 1891, with the synchronous barograph record below.

ords thus obtained, the instrument being placed in well 48, which has a depth of 40 feet and is tubed with 6-inch iron pipe down to rock, 37 feet below the surface. There was in this well at the time the first records were obtained 20 feet of water, and it had just been sunk. Water was first reached at a depth of about 25 feet, but after the drill entered the sandstone 2.5 feet the supply of water to the well considerably increased and the head raised 5 feet.

The financial assistance rendered in this investigation by the Weather Bureau, through the U. S. Department of Agriculture, made it possible to have twelve special recording instruments constructed for the purpose of this study, one of which is shown in Fig. 16. The instrument consists of a drum, carrying a record sheet, which is driven by a double marine eight-day clock movement in ten of the instruments, and a one-day movement in the other two. A copper float connected with a lever working upon conical bearings transmits the movements of the water surface to the pen. The arm of the lever to which the float is attached is one-third the length of that carrying the pen, thus producing a curve having an amplitude three times the normal. The fluctuations in most wells, however, have been found so large as not really to require this amplification for any but the smaller short-period fluctuations. The float consists of a hermetically sealed copper cylinder 6 inches long and 3 inches in diameter, loaded so as to float about one-half immersed in the water. The eight guard wires, shown in the figure, attached to the float are for the purpose of preventing surface tension from drawing it against the wall of the well and thus interfering with its free movement.

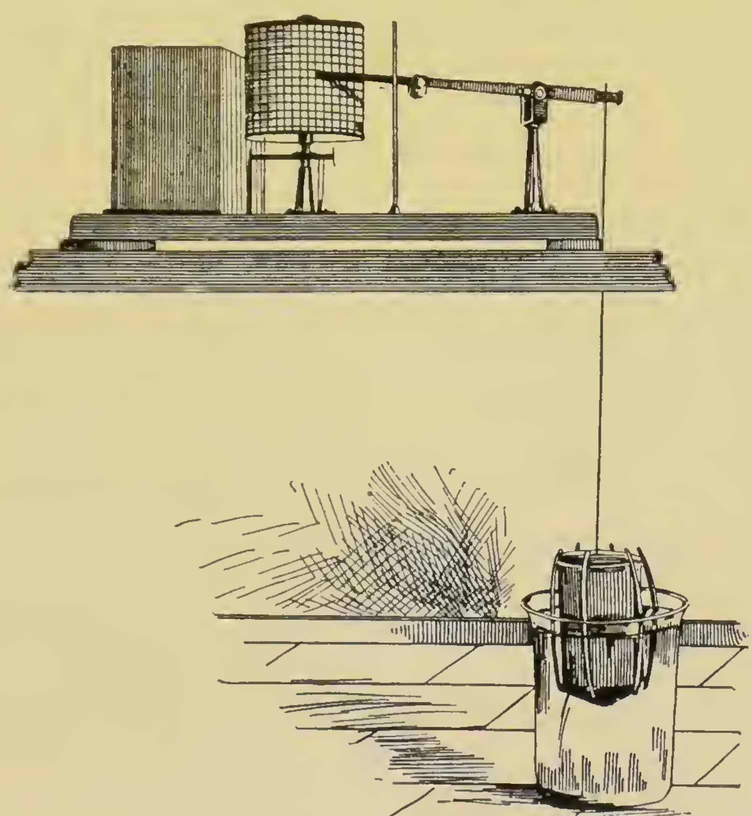

FIG. 16. Self-recording apparatus for registering fluctuations of water-level in wells.

While these instruments have answered very well for the hasty preliminary study for which they were designed, there are several im-

NOTE.—It is due to the manufacturer of these instruments, Mr. Henry J. Green, to say here that, considering the few weeks he had at his disposal for the construction of them, and the lack of specific details to guide him, the order was exceptionally well filled.

portant improvements required in them before they are capable of yielding exact records. As some of the imperfections referred to affect the results to be reported here, they will be pointed out in this place. In the first place, through an oversight, due to great haste in the construction of the pieces, no provision was made for easily adjusting the pen to the exact minute on the record sheet when a new one was put in place, and this has rendered it difficult to exactly combine the records so as to show the true time relations existing between the fluctuations of the different wells. In the second place, the screw movement by which the clock is coupled with the drum introduces a periodic error which throws the recorded events slightly out of their true time, but is so small as to seriously affect only the short-period fluctuations, and time has not permitted the application of any correction for it. This method of connection also introduces a third source of error by the considerable slack movement which it necessitates, and to overcome which no provision was made. In setting the clock the drum could be placed, of course, so as to take up all slack, but the errors introduced from this source come through any jar which the instrument might sustain, and in some cases might exceed one hour in time. These facts should be constantly borne in mind when considering the continuous records presented in this report.

THE COMPLEX CHARACTER OF FLUCTUATIONS TO WHICH THE SURFACE OF GROUND-WATER IS SUBJECT.

It is proposed to enumerate here, as preliminary to the presentation of the results which have been secured through the self-recording instruments and associated studies, some of the conditions which affect the level of ground-water, or may be expected to do so.

Possible secular changes in the level of ground-water.

It is a common remark made by many of the older settlers of this state and of Illinois, that the water stands permanently lower in the wells than it did in earlier times, and that many tracts of land which it was then impossible to get upon with a team are now hard enough to do so without difficulty. Without attempting to assign a cause for these supposed or real changes in the level of the ground-water, attention may be called to some changes now in progress tending to produce such alterations as that referred to.

In those sections of country undergoing secular changes of level due to movements of the earth's superficial strata, it is evident that all artesian basins experiencing any differential movement that would alter the relative height of the supply and drainage portions must tend to have established new drainage rates for them, and if the drainage portion of such a basin is being progressively lowered, relatively,

by any cause, while the mean percolation of rain into it remains the same, the level of the ground-water would tend to progressively decline.

Then again the depression, by surface erosion, of river beds or the outlet of lakes into which the ground-water of the surrounding highlands drains, must have a tendency to increase the drainage gradient and hence to lower the level of ground-water until equilibrium is established between the drainage and the mean annual percolation.

The water which percolates into the ground and again emerges from it carries away, both in solution and in mechanical suspension, large quantities of the rock constituents with which it has come in contact; and this, unless counteracted by other changes, must tend to develop an increasing porosity or widening of the passageways through which the water moves, and so to decrease the resistance to drainage and hence to lower the general level of ground-water in the region so affected.

If in any considerable tract of country the mean surface consumption of water is increased by a material increase in the annual production of dry matter per acre in the form of vegetation, there must necessarily be a decrease in the total drainage from that section, and for this reason a tendency to develop a lower stage of water in the ground, and through this a drying and hardening of marsh lands such as has been referred to. When it is stated that experiments conducted in England and Germany, and also at this station, all agree in showing that as much as 325 pounds of water are required to be withdrawn from the soil by the roots of plants in the production of each pound of dry matter, it is evident that to double the mean annual production of dry matter in a country must have an appreciable effect upon either the superficial or underground drainage from that region, and if upon the underground drainage, to lower the height of ground-water there and through this to lower the level of lakes, and to harden the marshy lands.

Short-period changes in the level of ground-water.

As has already been pointed out, seasonal and annual changes in the amount of water which falls upon the surface of the ground and percolates into it, have a tendency to develop stages of high and low ground-water in regions so affected.

Since changes in temperature very materially influence the viscosity of liquids, and since variations in the viscosity affect the flow of water through narrow passages like capillary tubes, it may be expected, as will be shown in another place, that both seasonal changes in soil temperature and mean annual ones also exert an influence in developing fluctuations in the level of ground-water through a modification of the rate of percolation and the rate of underground drainage.

Oscillations in the level of ground-water.

Besides the changes in the level of ground-water already pointed out, its general surface is further subject to extremely numerous oscillations of small extent, some of which are almost microscopic in amplitude; indeed, the times of even approximate quiet appear to be extremely rare. The equilibrium of the water in the capillary soil spaces above the surface of the ground-water is so unstable that apparently the slightest cause is sufficient to upset it, causing the water to flow out into the non-capillary spaces, but only to be returned again, often on a moment's notice. There appears to be a zone of soil particles of undetermined depth into and out of which there is a constant ebb and flow of water. The observations to be presented show that oscillations of atmospheric pressure of almost every character affect this underground water-surface. The longer period barometric changes associated with cyclones depress or raise the water-surface, as the case may be; the shorter period changes, which accompany thunderstorms, are registered there, and there are movements which are coincident in time with the semi-diurnal barometric changes. The diurnal changes in soil-temperature, under favorable conditions, produce corresponding rises and falls of the water-surface; and the passage of a train, even where the water is 20 feet below the surface, causes the non-capillary spaces to fill up and empty themselves again as the moving weight approaches and recedes. This ground-water ocean-surface, therefore, like that of the open sea, knows never one moment of rest. The geologic and agricultural significance of these movements must be very great, for here is a water washed zone of rock and soil, having the combined area of all land above ocean level, unless we must except those of the polar zones, which is alternately flooded with water and then exposed to air; and this zone rising and falling through greater and lesser distances, according to the secular and short period changes in the level of the ground-water, must greatly exaggerate the solvent power of soil water over what it would be did these oscillations not exist.

INFLUENCE OF BAROMETRIC CHANGES ON THE RATE OF FLOW FROM SPRINGS, ARTESIAN WELLS, AND TILE DRAINS.

Three of the self-recording instruments referred to were placed, one upon a spring at Whitewater, Wis., one upon an artesian well 300 feet deep situated one-half a mile distant from the spring, and the third so as to register any change which might occur in the rate of flow of water from a tile drain on the Experiment Station Farm.

The method of enabling the instrument to record changes in the rate of flow of water is illustrated in Fig. 17, which shows how it was placed in the spring at Whitewater. The spring in question was encased in a wooden cylinder 3 feet in diameter and the water brought

by it discharged through a 1¼-inch gas pipe, 4 feet long, into a vat used for setting milk cans in. The top of the spring curb was covered and the instrument placed as represented in the figure. In the case of the artesian well the principle was the same, for the well discharged from the side of the 6-inch tube through a ¾-inch gas pipe a few inches long, and the float rested directly upon the surface of the water, which stood at all times above the level of the discharge. In the case of the tile drain, the water flowed into a receptacle which had an orifice near the bottom, whose capacity could be altered so as not to allow the receptacle to become full and overflow the top. In all of these cases any change in the rate of flow of water from the ground would produce a change in the head of water discharging through the respective pipes, thus causing the float to rise or fall as the rate of flow increased or decreased.

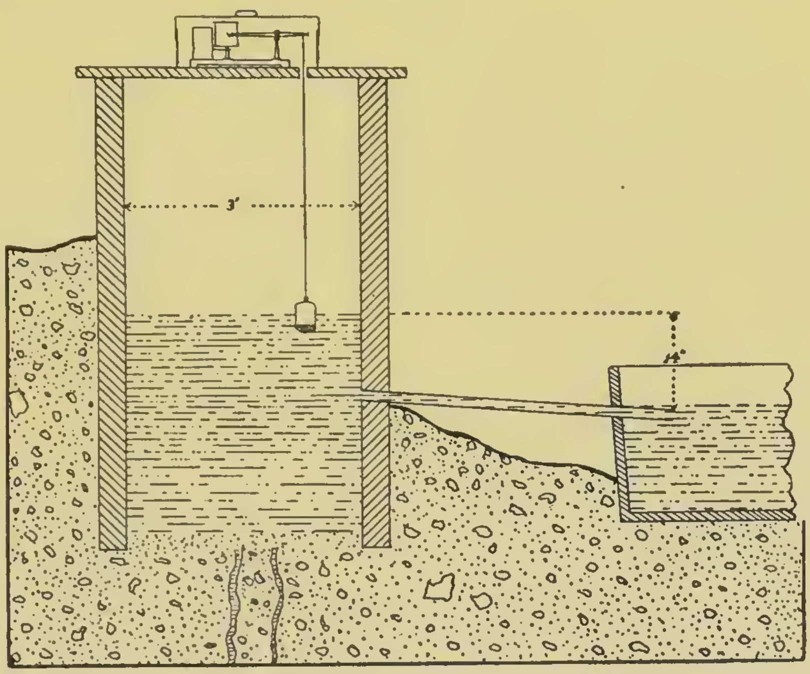

FIG. 17. Method of recording changes in the rate of flow of water from drains and springs.

A facsimile of the synchronous curves obtained from the spring and from the well during two and one-half days is shown in Fig. 18, from which it will be seen that while they are not alike in the minuter oscillations, there is yet a remarkable agreement between them.

There was no barometer record kept at the place where the well and spring are, but the barograph records at the Experiment Station are available for comparison with these curves, but it must be borne in

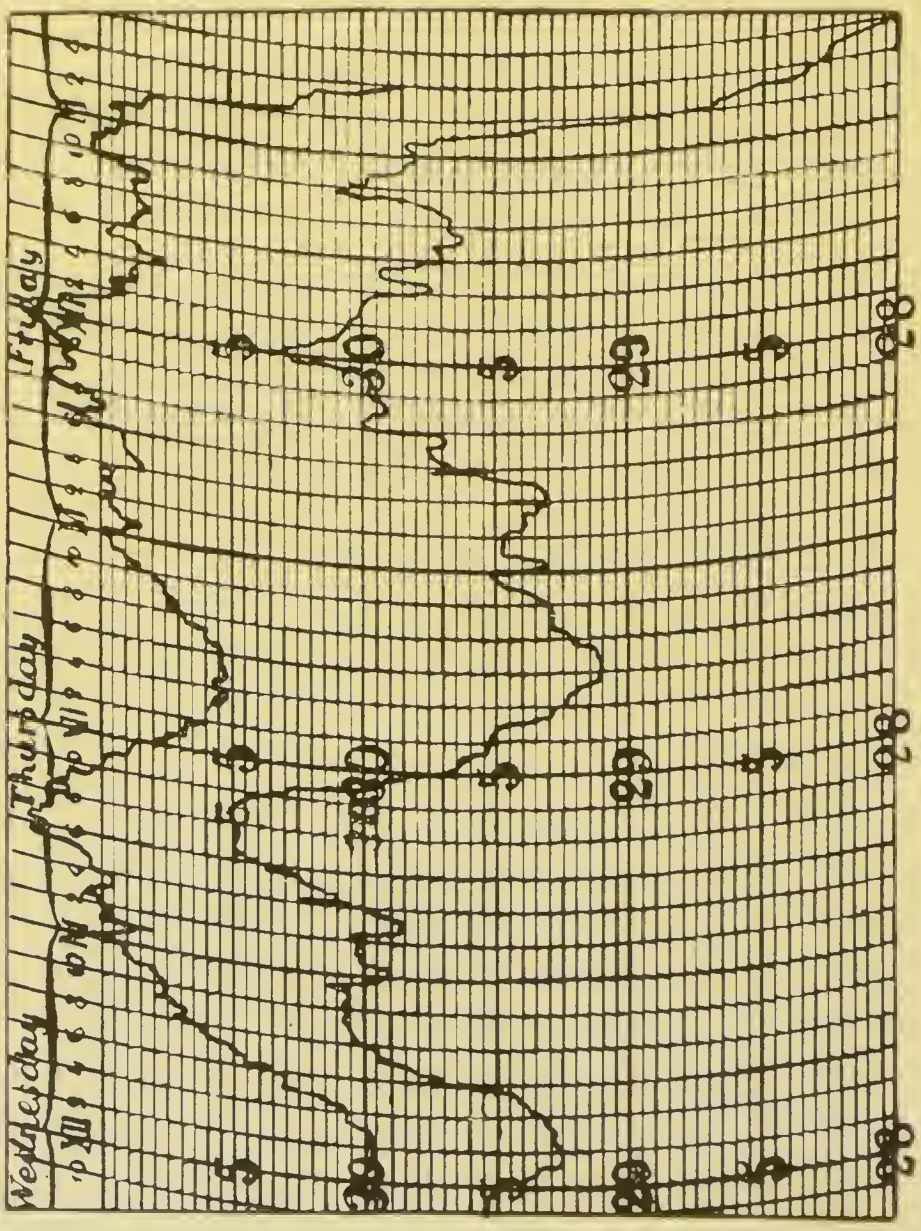

FIG. 18. Synchronous records, showing variations in the rate of flow of water from a spring and from an artesian well at Whitewater, Wis.

mind that the barograph is situated 45 miles to the westward of the locality under consideration. In Fig. 19 the records of the barograph and that of the spring for May 4 to 16 are placed in juxtaposition, the minor oscillations of the spring being omitted. It requires only a glance at these two curves to see that they are remarkably concordant, considering that they are separated by an interval of 45 miles and that the curves are in themselves so complex. It is true that the changes recorded by the barograph fall a little earlier than the corresponding ones produced by the spring, but as the barometric changes are progressive from west to east a certain interval should be anticipated, even were there no lagging due to other causes.

So, too, when we compare the barometric curve with that obtained from the tile drain referred to, as shown in Fig. 20, it will be seen

that there is here also a close agreement between most of the marked curves which the barograph shows and those produced from the fluctuations in the rate of discharge from the tile drain. The rapid in-

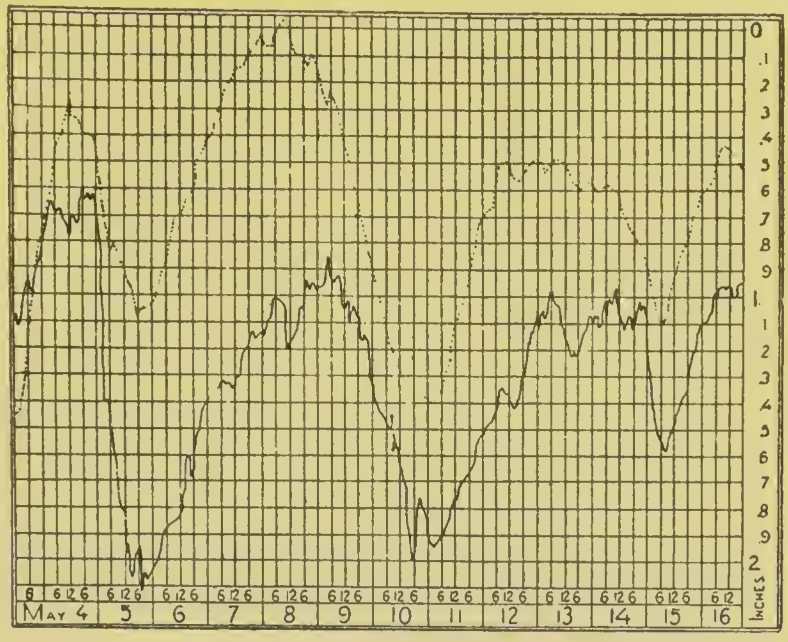

FIG. 19. Fluctuations in the head of a spring at Whitewater, Wis., from May 4 to May 16, and the barograph record at Madison for the same period. Both reduced to natural scale.

crease in the rate of discharge on Sunday is due to percolation resulting from the rain of 1.10 inch falling during Saturday night and Sunday.

The smaller short period fluctuations shown on the drain curve are a portion of them barometric, but not seen to be so because the amplitude of the barometer curve is too small to show their equivalents upon it; the very sharp shortest period curves are many of them due to the pumping action of the wind, which tended to suck air either out of or into the drain and thus modify the rate of discharge.

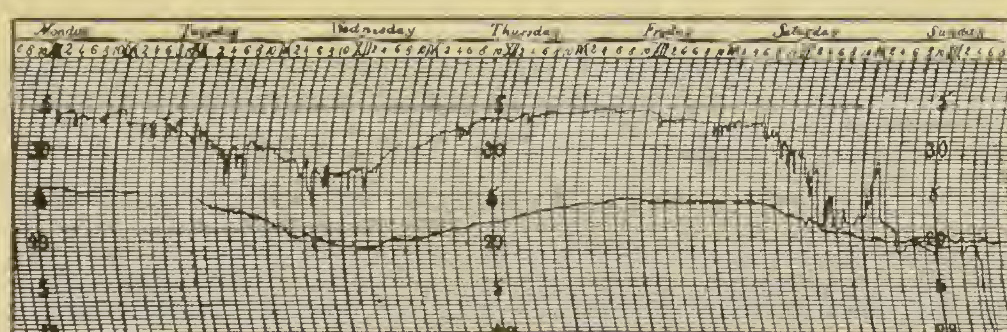

FIG. 20. Synchronous changes in the rate of discharge of water from a drain, and the barometric changes during one week.

In the case of the spring under consideration, the barometric changes which occurred during the intervals when the records were kept caused the head to range from less than 12 inches to more than 14 inches, and this would give a theoretical variation in the rate of discharge amounting to 8 per cent., the water flowing this much faster during one interval of low barometer when compared with that tak-

ing place during an immediately preceding high barometer. In the case of the tile drain, with the water discharging from the gauge under a head of .585 inch, a sudden rise in the barometer amounting to .1 inch decreased the head in the gauge almost as suddenly .15 inch, and considering the velocity of discharge to vary as the square root of the head, the water was discharging under the high pressure 15 per cent. less rapidly than previous to the change of atmospheric pressure.

The water supply at the waterworks for the city of Whitewater is derived from an artesian well 979 feet deep, the water flowing into a reservoir 106 feet in diameter in which there is an overflow pipe having an inside diameter at the top of 9.75 inches. The pumps are coupled directly to the well in such a manner as to draw upon the reservoir when the rate of flow from the well does not equal that of pumping. Through the kindness of the proprietors, Messrs. C. G. Gray & Co., I was permitted to place one of my instruments in the reservoir so as to determine whether or not this well was subject to variations in the rate of flow analogous to those observed in the spring and shallower well near by already referred to. To obtain the rate of flow of water from the well the float of the recording instrument was placed upon the water in a cylinder which was partly submerged in the reservoir, the bottom of the cylinder being perforated with several small holes so as to establish communication with the water in the reservoir without allowing the float to be disturbed by wave action.

During the pumping, which occurred once daily, the water was lowered in the reservoir from 2 to 4 inches, and the instrument was so adjusted as to record the length of time required for the reservoir to regain its original level after pumping, and to show any change of head which might occur while the reservoir was overflowing.

One of the eight-day instruments was first placed in the reservoir, and Fig. 21 shows a portion of the record obtained with it, where it will

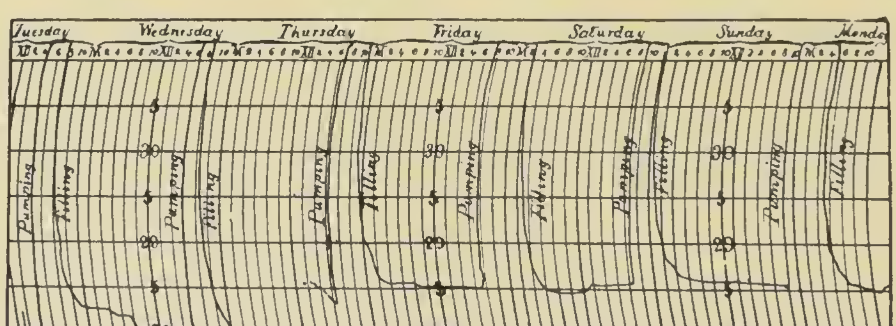

FIG. 21. Changes in the rate of flow from the artesian well at the city waterworks, Whitewater, Wis.

be seen that not only did the time required for the reservoir to regain its original level vary but also that this level did not remain constant

when once attained. It should be observed that the curve showing the rate of filling covers only the last portion for each day.

In order to be able to measure the time of filling more exactly one of the one-day instruments was substituted for the one first used, and a record obtained during 10 consecutive days, with results as given below:

Table showing variations in the rate of flow of water from the artesian well at the city waterworks, Whitewater, Wis., from May 31 *to June* 9, 1892.

	Cu. ft. per min.
May 31, well discharged 1103.09 cubic feet in 77.82 minutes,	= 14.175
June 1, well discharged 1103.09 cubic feet in 71.44 minutes,	= 15.441
June 2, well discharged 1103.09 cubic feet in 75.27 minutes,	= 14.655
June 3, well discharged 1103.09 cubic feet in 72.71 minutes,	= 15.171
June 4, well discharged 1103.09 cubic feet in 76.54 minutes,	= 14.412
June 5, well discharged 1103.09 cubic feet in 79.09 minutes,	= 13.947
June 6, well discharged 1103.09 cubic feet in 72.71 minutes,	= 15.171
June 7, well discharged 1103.09 cubic feet in 76.54 minutes,	= 14.412
June 8, well discharged 1103.09 cubic feet in 73.99 minutes,	= 14.909
June 9, well discharged 1103.09 cubic feet in 72.71 minutes,	= 15.171

On June 1, 7, and 8, at the time of sudden showers, the water-level in the reservoir changed so as to carry the float up through .1, .5, and .4 inch respectively, and this when the water had been overflowing at its normal height during several hours. The shower when the water rose more than .5 inch was a very heavy one, but all of them were of short duration. As the overflow was within three feet of the place occupied by the instrument it does not appear probable that any wind action, by forcing the water to that side, could have produced the change of level observed, and that this could have been the cause is rendered still more improbable by the fact that the water rose and fell so as to give a steady curve, as shown in Fig. 22. Neither

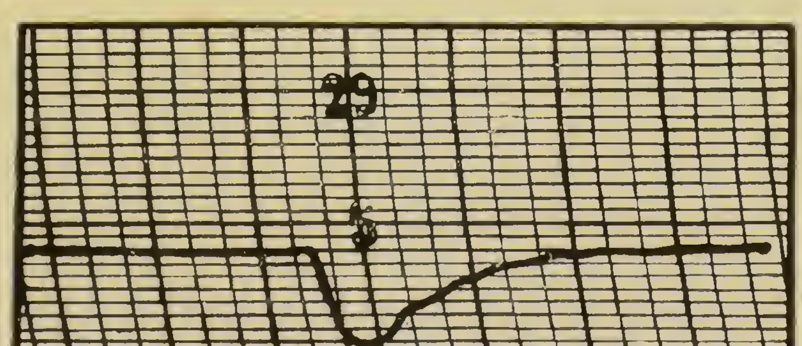

Fig. 22. Sudden changes in the flow of water from the artesian well at the city waterworks, Whitewater, Wis. Natural scale.

does it appear possible that any shower could have increased the head to the extent observed, by direct precipitation into the reservoir, for the overflow pipe was never carrying water at nearly one-half of its full capacity. If no such explanation as has been suggested is admissible, the conclusion must be that these deep wells are subject

to sudden increases in flow such as have been shown to be true of the spring, the drain, and the shallow artesian well referred to.

It should be observed here also that the changes in the rate of flow recorded by the eight-day instrument are coincident in time, and also in character, with the changes which took place in the spring and other well in the same vicinity, and it would appear, therefore, that barometric changes exert a far reaching influence upon the underground drainage coming from any and all depths below the surface. The magnitude of this influence is so great also that the aggregate increase or decrease in the flow of water from large subterranean drainage areas, as low and high pressure waves travel over them, must be absolutely very great and, it would seem, capable of registration by suitable instruments on very many, if not upon all, rivers, and possibly all lakes as well.

BAROMETRIC OSCILLATIONS IN THE LEVEL OF WATER IN WELLS.

The evidence is overwhelming that barometric changes exert a very marked and nearly if not quite immediate influence upon the level of water in a well. That sudden and large changes in the barometer are closely associated with marked changes in the level of water in wells is strongly suggested by the facsimile curves shown in Fig. 15, already referred to on page 40, but here the amplitude of the barometer is too small to make a satisfactory comparison between them in any except the general features.

In order that a closer comparison might be made in this particular, the two one-day instruments were placed one upon well 48 and the other upon the air barometer represented in Fig. 23, which was constructed for this purpose and to ascertain whether or not some of the short period fluctuations shown both by the wells and by the spring and drain might not be due to a pumping action of the wind.

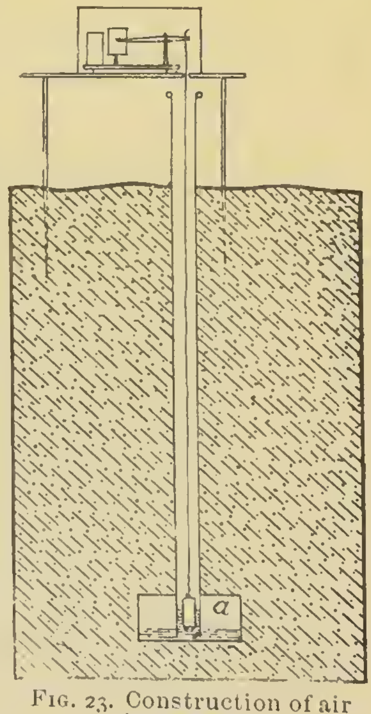

FIG. 23. Construction of air barometer.

This instrument, apart from the recording portion which has been described, consists of a galvanized iron cylinder, 4 inches in diameter and 8 feet long, to the lower end of which is attached a cylinder of the same material 18 inches in diameter and 8 inches deep; this larger cylinder confines a quantity of air which, by its changes in volume, alters the level of the water shown and thus causes the float to rise and fall with each change of atmospheric pressure. The air receptacle is placed six feet below the surface of the ground and the earth filled in over it so as to avoid marked temperature fluctuations. The instru-

ment thus constructed proved to be quite satisfactory for the purpose designed, and has an amplitude five to six times that of the mercurial barometer.

How closely in accord the fluctuations recorded by this instrument

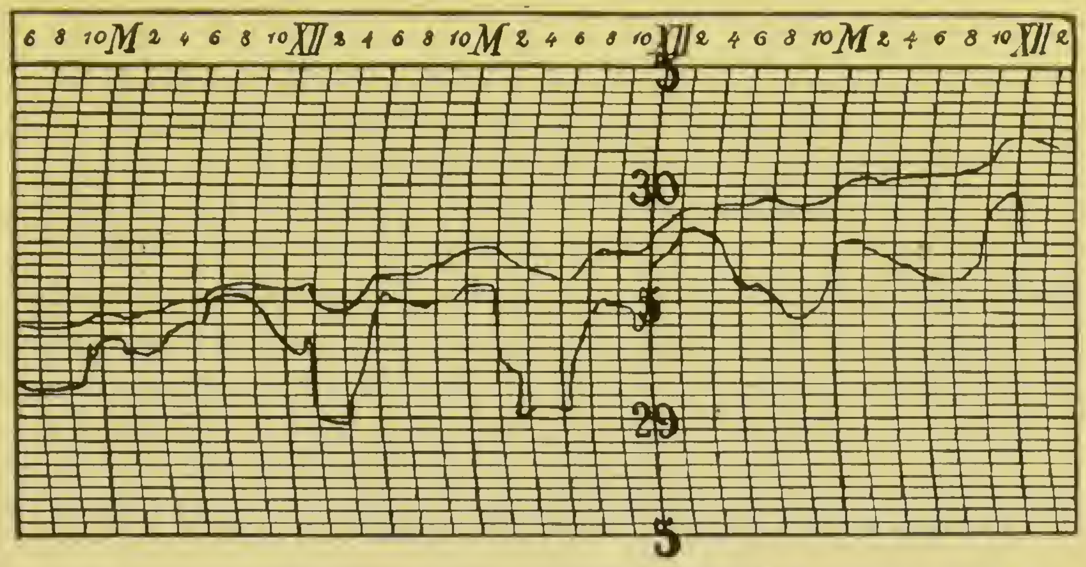

FIG. 24. Synchronism of barometer and well changes as recorded by one-day instruments.

and by the one placed upon the well are will be seen from Fig. 24, which shows the curves produced during the 10 hours closing 7.50 a.

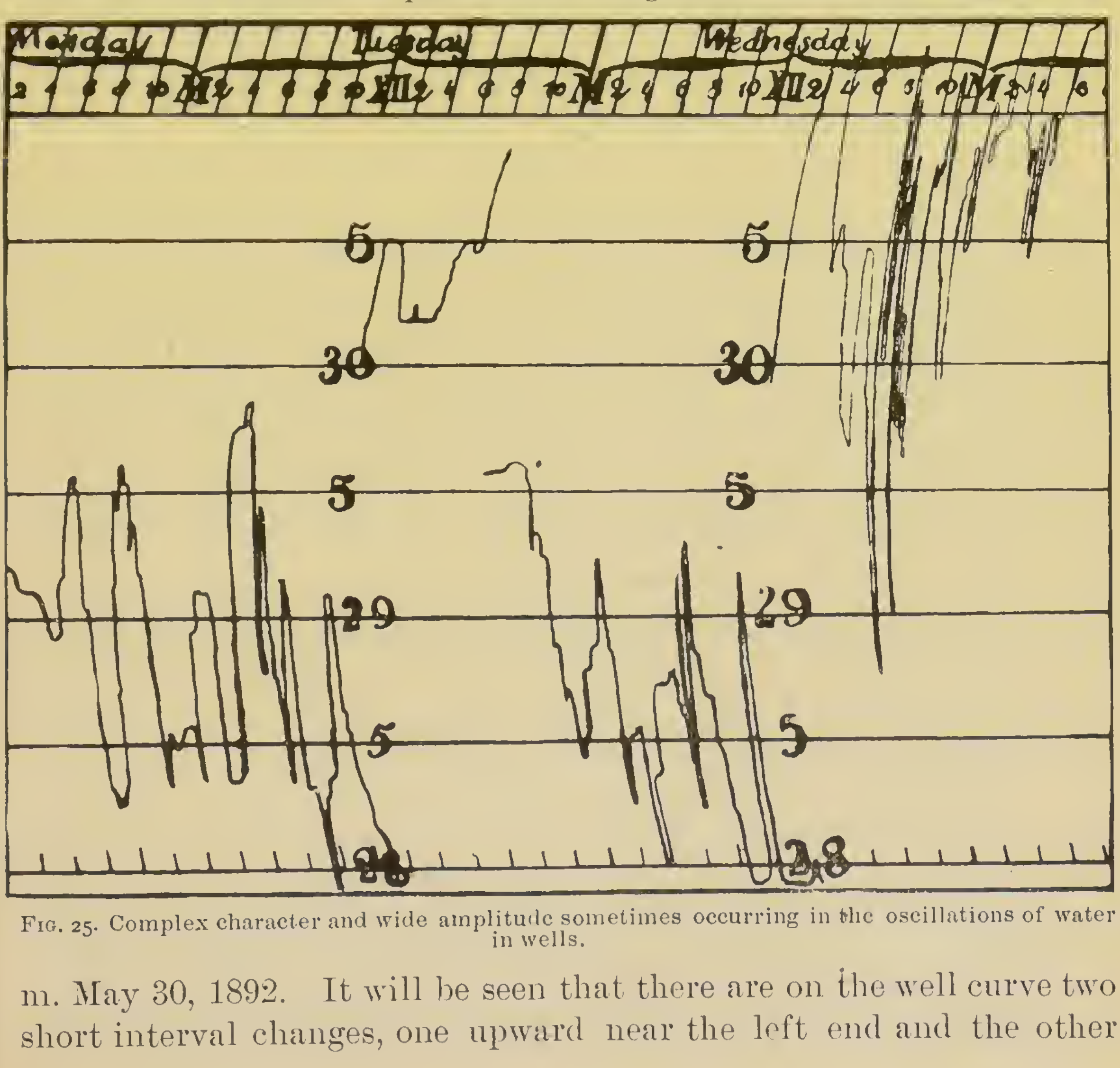

FIG. 25. Complex character and wide amplitude sometimes occurring in the oscillations of water in wells.

m. May 30, 1892. It will be seen that there are on the well curve two short interval changes, one upward near the left end and the other

downward to the right of the center, which have no analogous ones in that of the air-barometer, otherwise there is an extraordinary agreement in all features except amplitude.

At times these barometric fluctuations are both of extreme amplitude and of great frequency also; this is clearly shown in Fig. 25, where the amplitude was so large as to require the pen to be set over four times between 2 p. m. Monday and 6 a. m. Thursday, and at

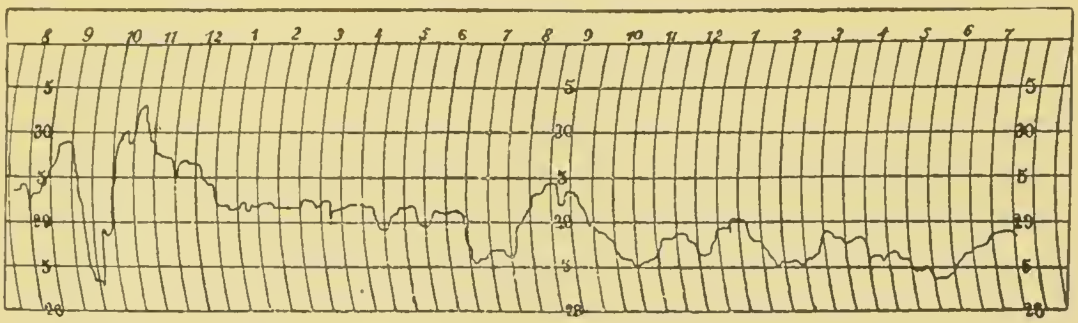

FIG. 26. General character of fluctuations of water in well 48 during 24 hours.

intervals during this period the changes were so rapid as to force the lines close together. The general frequency of these changes are better shown in Fig. 26, which is a tracing of the curve produced during 24 hours ending April 30, 1892, by well 48.

The synchronism of movement which the ground water in different wells in the same locality exhibits is shown in Plates II to V, where the curves are reproduced so as to show the actual changes of level as they occurred from day to day.

It should be borne in mind in studying these plates that the direction of the movement of the water surface in the well was opposite to that shown by the curve, a descent of the curve across the page meaning a rise of water in the well and *vice versa*, and this is true for all of the curves obtained with the instruments used. Since a rise of the barometer is associated with a tendency of the water to fall in the well and a fall of the barometer with a tendency to rise, the method of mounting the pen causes that of the barograph and that of these recording instruments to move in the same direction at the same time.

It will be seen from a study of these plates that nearly all of the marked sudden barometric changes are shown, in a greater or less degree, on nearly all of the wells. The long period barometric oscillations are usually recorded by the wells, but these are much more obscured by the percolation of rain into the ground and by the general lowering of the ground-water surface by subterranean drainage. That this should be so is plain, because it very often happens that, at a given well, the downward descent of the water-level, due to drainage, is exactly compensated for by the rise due to a fall in the barometer, and in such a case the tracing for that period will be horizontal, while in that of another well in which the water chances to be rising

at the same time in consequence of percolation, the barometric effect will be added to that of percolation, so that while the first well shows no curve corresponding to that of the barometer the one for the second shows it in an exaggerated form. The evidence of the influence of long period barometric oscillations must therefore be sought, generally, in a variation in the mean rate of change in the fall or rise of the ground-water surface.

It appears to be a general rule that the long period barometric oscillations, and perhaps all barometric changes as well, exert a greater influence upon the water of the deeper than upon the shallower wells, and this, too, should be expected from what has been said, because the deeper wells are less affected by local percolation into them and the reverse action which is a consequence of it.

SEMI-DIURNAL OSCILLATIONS IN THE LEVEL OF WATER IN WELLS.

It has already been pointed out that the water of wells exhibits a tendency toward diurnal oscillations, the water, as a rule, standing higher in the morning or else not having fallen as rapidly during the night. The continuous records obtained from the wells, from the spring, and from the drains show very clearly, at times, that the level of water in the non-capillary spaces in soil is subject to regular semi-diurnal oscillations, as a careful inspection of the various plates will prove.

To render these semi-diurnal changes more apparent, I have selected a week when there were no large barometric changes and have taken a well in which the water surface was nearly stationary so far as drainage and percolation are concerned. The week selected was that ending July 11, 1892, and the well was No. 33. Side by side with this the curve produced by the air-barometer has been placed, and with it also that of the Richard barograph of the same date. The curve of the Richard barograph is magnified about six times and was constructed as follows: The record sheet was passed through the field of a compound microscope, provided with an eye-piece micrometer, and magnifying 43 diameters. The changes in the position of the barometric curve on the record sheet were measured at the crossing of each of the two-hour lines by bringing one end of the micrometer scale always to the lower side of a distance line and reading the distance to the under side of the barometer curve in divisions of the micrometer scale, and as fifty divisions of the micrometer just spanned the distance lines it was possible to read the changes very closely and to plot them on a large scale very accurately. The two barometric curves and that of the well are shown on the upper portion of Plate VI, where the coincident semi-diurnal changes are very evident on nearly every day of the week. It will be seen that there is a minor minimum falling from 9 to 11 p. m., and a major one

falling from 7 to 10 a. m. On the same plate there have been plotted the curves of the same well for the two following weeks, and also that of the air-barometer for the last week, and it will be seen, when these are all compared, that, while the more numerous short period barometric fluctuations tend to obscure the semi-diurnal ones, these are evidently there and in the same relative position with respect to time.

The 300-foot artesian well at Whitewater and the spring also show these same semi-diurnal fluctuations, but the long barometric oscillations were so great during the weeks when the records were kept that the semi-diurnal oscillations are much obscured by them, and there they appear to fall at about the same times of the day also as they do with the shallower wells at Madison.

I find in the Report of the Transactions of the British Association for 1883, p. 405, the following, under the subject—"On the Attractive Influence of the Sun and Moon Causing Tides, and the Variations in Atmospheric Pressure and Rainfall Causing Oscillations in the Underground-Water in Porous Strata." By Isaac Roberts, F. G. S.:

> The investigations have been made at Maghull, which is an agricultural district about 8 miles to the northeast of Liverpool, and relate to movements in the underground water of the Triassic rocks, which lie beneath the surface of the ground. The water in these rocks is by capillarity made to form an inclined plane toward the sea, which, at the point referred to, has its surface 60 feet above mean sea level. The water plane was shown to be in a state exceedingly sensitive to the following influences, namely, atmospheric pressure, lunar attraction, and solar attraction.
>
> In order to determine the relative extent of these and other disturbing influences upon the water plane, an artesian well was sunk in the Triassic rocks to a point below mean sea level and the rise and fall of a column of water 60 feet in height, freed from the friction in the rocks, was used as the means of registering these disturbances in the water plane, by using a mechanical combination of a float and drum, caused to revolve by clockwork, to trace a curve upon the diagram paper.
>
> The curve showed the extent, from moment to moment, of the atmospheric variations, and also the effects of the attraction of the sun and moon upon the water plane in producing oscillations in the first case and true semi-diurnal lunar and solar tides in the latter case. The effects of rainfall were also shown on the diagram.
>
> It was also shown that there were periods when all of the forces which have been named were in equilibrium, the water plane remaining in a state of perfect quiescence during those periods.

The statement to which attention is here called especially, is the one ascribing certain fluctuations in the level of the water in this well to both solar and lunar tidal disturbances. I have not, as yet, been able to learn whether the paper to which the above report refers has been published or not, and do not, therefore, know the character of the evidence upon which these statements are founded. There is certainly no unequivocal evidence presented by any of the curves obtained in the investigation here which would lend support to the view that a lunar tidal effect has been exerted large enough to be recorded by the instruments used. The apparently entire absence of

any progressive change in the time of day at which the maxima and minima occur is the strongest evidence which can be presented against the view that a lunar influence is here recorded. There is, of course, nothing in the time relation which would disprove a solar tide; but if a solar tide is admitted to be recorded, there then appears no reason why, at times at least, a larger one should not also be recorded, having the proper time relations for the moon. Some of the wells at Madison, included in this study, are deeper than the one used by Mr. Roberts and extend below the level of Lake Mendota in the Potsdam sandstone. The still deeper wells at Whitewater also find their water in a porous sandstone, so that the only condition apparent, which is fundamentally different in the well of England, is the close proximity of an oceanic body of water which is, itself, subject to tidal fluctuations. This being true, one is led to suspect that in case the wells in question do exhibit both solar and lunar tidal oscillations they, in some manner, may be a reflex of the oceanic tides.

We are told, however, that the well in question is some 8 miles distant from the sea and that the water "*is by capillarity* (the italics are the writer's) made to form an inclined plane toward the sea, which at the point referred to has its surface 60 feet above mean sea level." Now, were it true that the water is sustained in the well by capillarity to a height of 60 feet in the soil, which the writer knows of no sufficient evidence to prove, it is then required that a rise and fall of the ocean level permits capillarity to increase the height of the soil water when the length of the water column is diminished by the rise of the tide on the coast, but this implies that a force which is able to carry the water to a greater height in the soil is unable to retain it there after it has done so, for otherwise the level of the water in the well would not be affected.

If the oceanic tidal wave is transmitted to the well it would seem that it must be the result either of a direct shock or, what is much more likely, through a deformation of the rock strata by the loading and unloading of the coast.

It had occurred to the writer before reading the notice of Mr. Roberts' results, that in case the superficial strata of the earth are subject to any deformation by tidal stress, the unequal strength of the confining beds of an artesian basin, or the change of volume due to warping such beds, if of equal strength, must necessarily be made evident by a change of level in any column of water sustained by the hydrostatic pressure of such a basin.

The calculated magnitude of these disturbances and of the barometric and tidal loading and unloading of continents and their margins given by G. H. Darwin, had led me to anticipate, for the tidal effect, a very pronounced oscillation of the water-level or pressure in the deeper

artesian wells having extended basins. If such oscillations do exist in any of the wells upon which the observations here detailed have been made, they are so masked by the semi-diurnal oscillations just de-

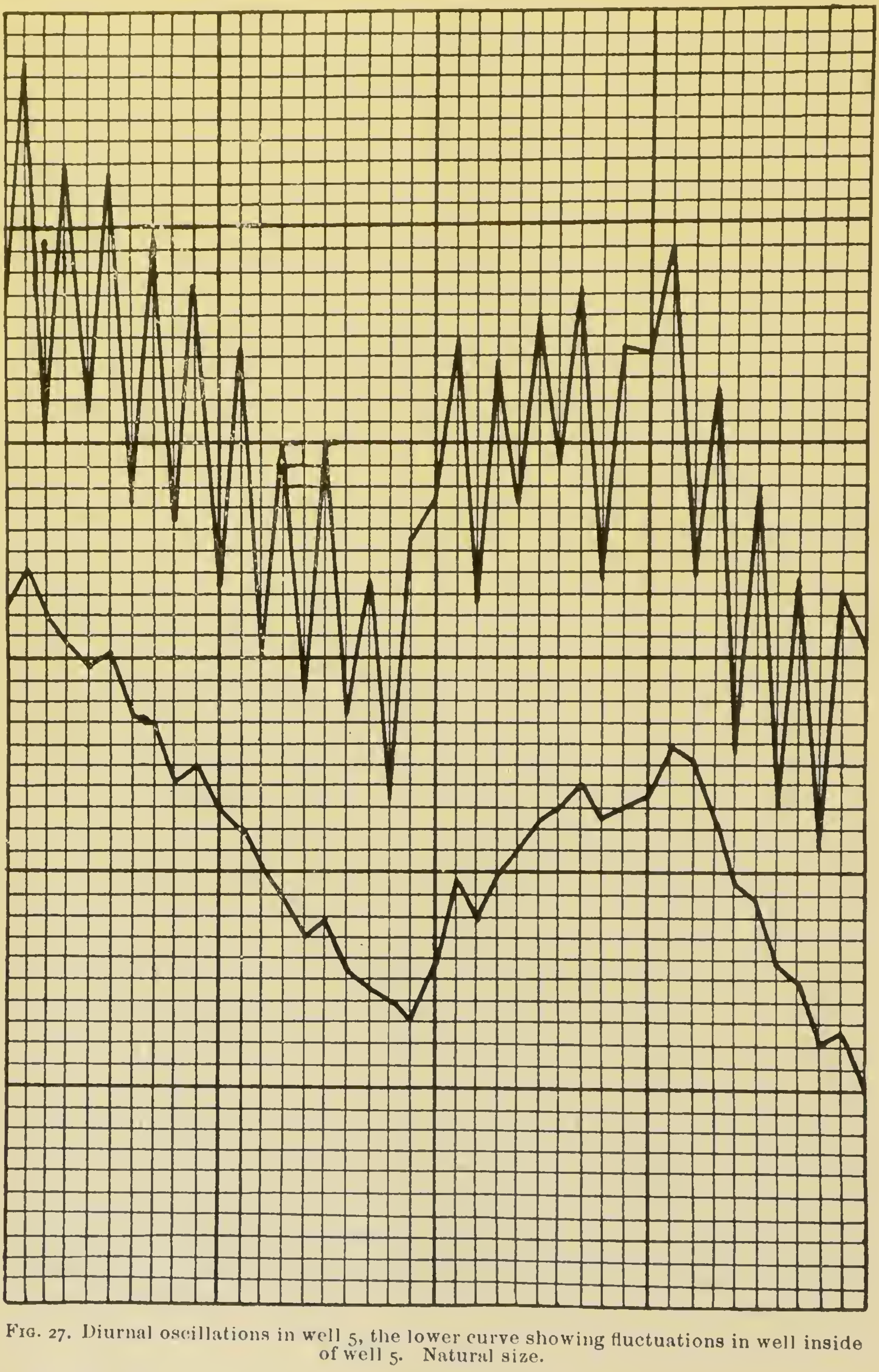

FIG. 27. Diurnal oscillations in well 5, the lower curve showing fluctuations in well inside of well 5. Natural size.

scribed, evidently not due to this cause, as to require a more critical registration and analysis of them than has been possible in this brief study.

INFLUENCE OF DIURNAL CHANGES IN SOIL TEMPERATURE IN PRODUCING CORRESPONDING OSCILLATIONS IN THE LEVEL OF GROUND-WATER.

The twice-daily observations recorded on Plate I and referred to on page 31 show very clearly that in certain wells and at certain times there is a marked diurnal change of level in the ground-water surface. In Fig. 27 is given a section of Plate I, natural scale, showing the diurnal changes in the level of water in well 5 during the days from July 18 to August 6, 1889. From this it will be seen that the water rose during the night and fell during the day to the extent of a full inch or more. The curve plotted below the one of larger amplitude shows the changes of level which occurred in the center of the same well and during the same time, the two sets of observations being simultaneous. The circumstances are these:

The ground-water level had fallen until well 5, now in question, was likely to become dry. In order not to lose the records it was deepened by boring a hole in the center and curbing it with sections of 5-inch drain tile in the manner represented in Fig. 28, which shows the two water surfaces, whose fluctuations are recorded in the last figure. The original well, having an inside diameter of one foot and a depth of 5.5 feet, was bricked up to within 2 feet of the surface and then finished with a section of sewer pipe, as shown in the cut, where the character and arrangement of the soil through which the well penetrated may also be seen.

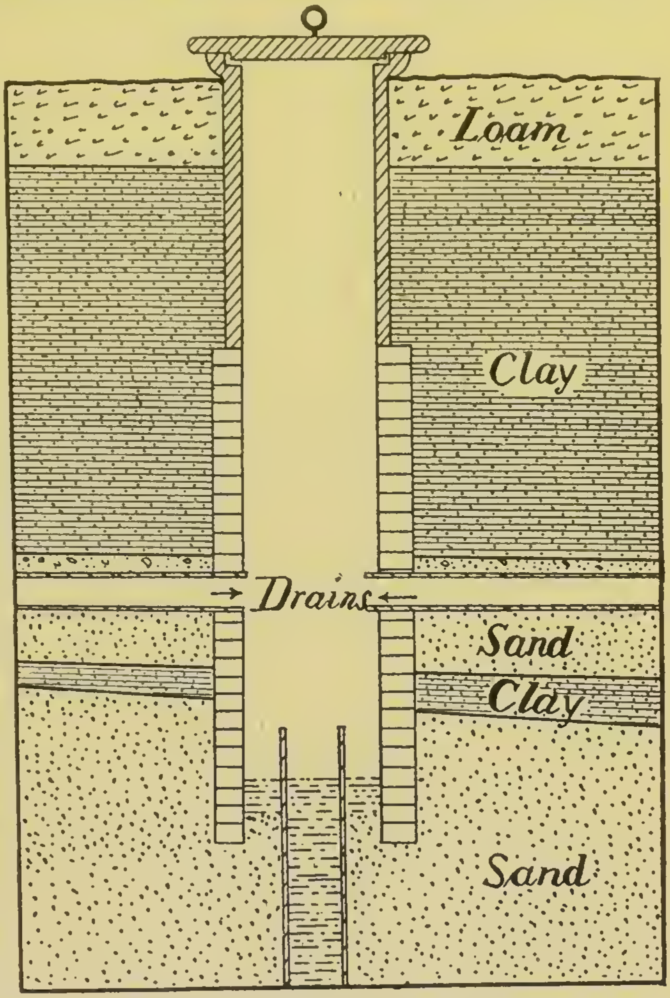

FIG. 28. Construction of well 5, and the character of the soil through which it penetrates.

The facts are, strange as it does appear, that under these conditions and in such close juxtaposition oscillations so unlike in their character as the two under consideration were produced simultaneously. The level of the water in the outer well oscillated so as to stand in the morning from .1 to .3 inch above the level of the water in the inner one and at night from .5 to 1.2 inch below that surface, and these differences were maintained with only the unglazed section of drain tile separating them. During the day, then, presumably, water

was flowing from the inner well over into the outer and larger one, while the fact that the water in the outer well rose to a height exceeding that in the inner one shows that some of that water at least must have come into the well from a level above the bottom of the outer well. As shown in Plate I, the large oscillations in this well became very pronounced and constant only a short time before it became dry, and the inner well did not take up the marked changes in level after the water fell below the bottom of the original well. No other well of this series, although constructed in the same manner, showed such marked oscillations as this one. Referring again to Plate I, it will be seen that several other wells did show them, but that there is something apparently very capricious about the starting and stopping of these oscillations. Wells 45, 43, 41, and 40 took on these strong oscillations just after they had been deepened, while well 44 did so without being deepened at all. Wells 40 and 43 oscillated in this marked manner only a few days, while well 41 did so from August 3 until after the middle of September. From the 3d of September until after the 15th all of the wells showed a tendency toward an increased diurnal fluctuation. When these fluctuations were first observed in the fall of 1888, as already referred to—the one in the corn exhibiting the greatest oscillations, while the one in the stubble showed least, as represented in Fig. 1—it was then thought that these differences in the magnitude of the oscillations might be due to differences in the daily amounts of water withdrawn from the soil by vegetation. The observations of the following season showed that this could not be the chief cause of the difference, for then well 5 was on a blue-grass sward with the grass cut short at the time the oscillations were most marked, while well 41, penetrating fallow ground, oscillated much more than did the wells on either side having corn growing about them. Another peculiar feature about these oscillations is the fact that during the years from 1888 up to the

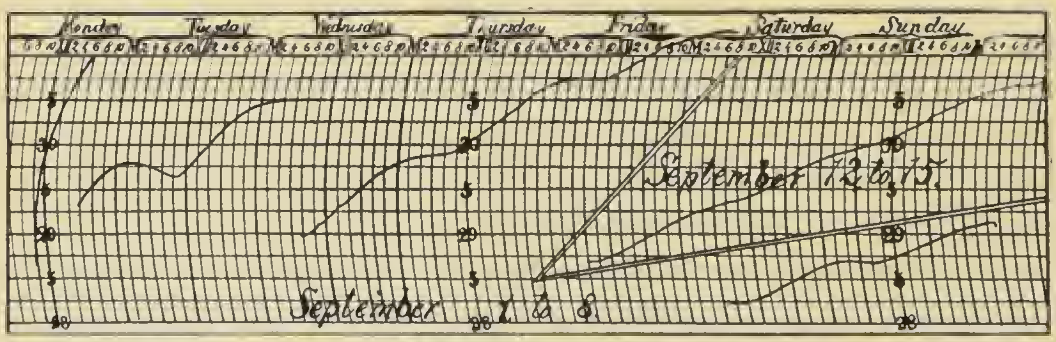

FIG. 29. Dying away of diurnal oscillations in well 5 from September 1 to 14, 1891.

present time no such marked changes in level of the water were revealed by twice-daily observations taken in the morning and evening until past or near the middle of July, from which time there is an advance toward a maximum, occurring some time in August and then

a dying away again until along toward the middle of October, when they again became inconspicuous.

In the fall of 1891 the improvised self-recording instrument referred to was placed upon well 5, September 1, just as the oscillations in question were beginning to die away, and Fig. 29 shows these changes from September 1 to 3 and again on September 12 to 14, when their amplitude had become almost inappreciable. In Fig. 30 are also plotted the curves for wells 42 and 44 and the drain from July 25 to 28, 1892, when these oscillations are beginning to become pronounced. It will be seen by referring to Plate V that these diurnal oscillations were beginning to be evident in the previous week.

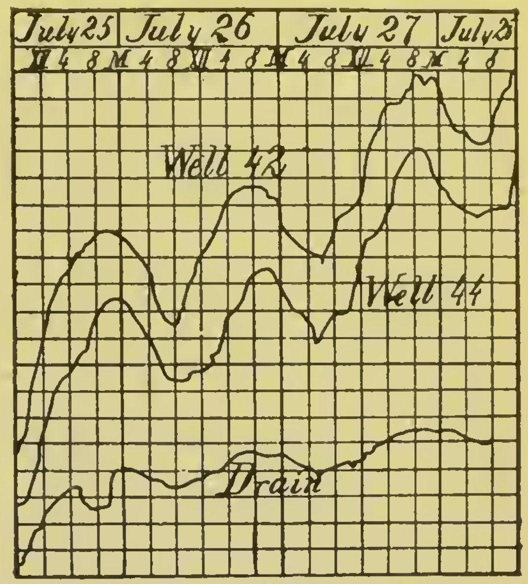

FIG. 30. Diurnal oscillations of water in wells and drain due to diurnal changes in soil temperature.

In the spring of the present year a galvanized iron cylinder 6 feet deep and 30 inches in diameter, provided with a bottom and water tight, was filled with soil, standing its full height above the ground in the open field. In the center of this cylinder and extending to the bottom, a column of 5-inch drain tile was placed and the soil filled in about it and packed as thoroughly as practicable. Water was poured into the cavity formed by the tile until it was full, and allowed to percolate into the soil so as to saturate it and leave the water standing nearly a foot deep in the well. When the water in this artificial well had become nearly stationary one of the self-registering instruments was placed upon it, the object being then to ascertain whether water thus circumscribed in a well would exhibit fluctuations at all analagous to those observed in ordinary wells, and the apparatus as used is shown in the engraving, Fig. 31. In order to avoid any complications due to percolation, the apparatus was provided with a cover which could be put on in times of rain and removed again during fair weather. The first records showed a small diurnal oscillation, and as the season advanced these increased in amplitude until

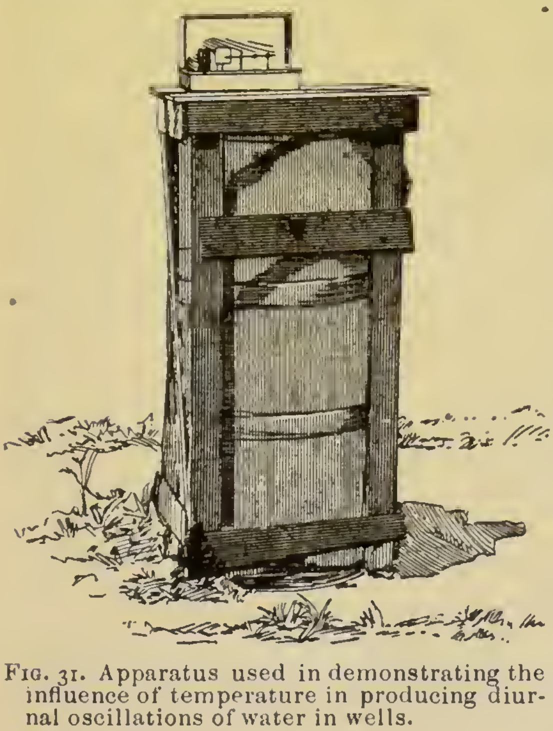

FIG. 31. Apparatus used in demonstrating the influence of temperature in producing diurnal oscillations of water in wells.

finally the water rose in the well during the day of July 8 1.8 inch and fell during the following night 1.84 inch.

After these diurnal oscillations had become so pronounced and so constant a series of thermometers were introduced into the side of the cylinder, extending to different distances from the surface, and a record kept of the changes in the soil temperature; and the result of these observations was to show that the turning points in the water curve fell exactly upon the turning points of the temperature of the soil in the cylinder. When this fact was ascertained, to show whether the correspondence in the time of the two curves was due to a diurnal cause, other than temperature, which had its turning points so related to those of the temperature as to cause the two to accidentally fall together, cold water was brought from the well and, with a spray pump, applied to the surface of the cylinder all around. The water was applied on a hot, sunny day just after dinner, when the water was rising in the well, and the result was an immediate change in the curve, the water beginning to fall in the well and turn the pen up. The water was then turned off, and the result of this change was to stop the fall of the water in the well, as shown by a change in the direction of the curve downward again. After the lapse of about another hour the water was again turned on, with the result first obtained, and again when the water was withdrawn the curve was once more reversed; a tracing of the curve obtained during these trials is represented in Fig. 32.

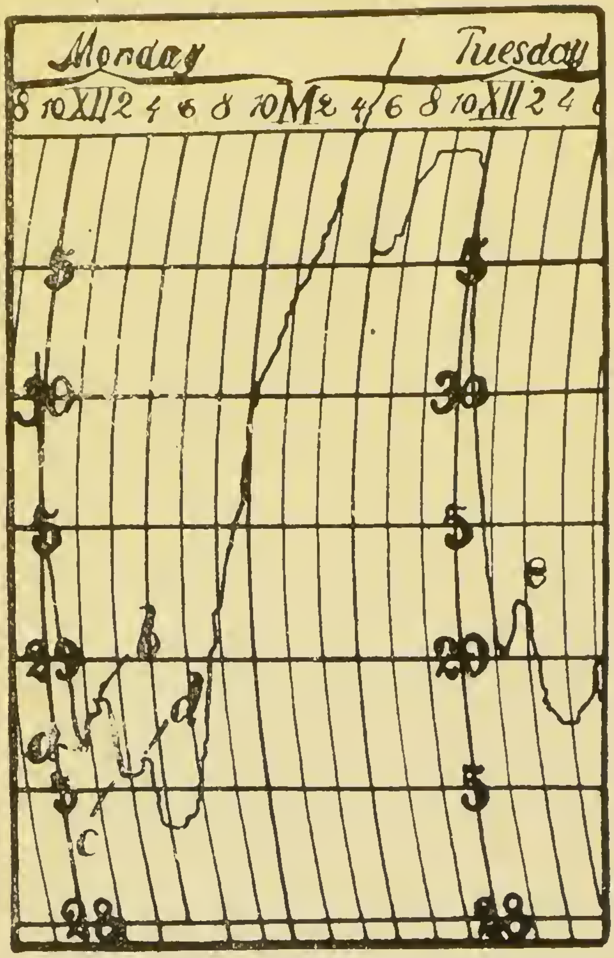

FIG. 32. Changes in the level of water in the well in the cylinder produced by pumping cold water on the sides of the cylinder; *a* and *c* show times of applying the water, *b* and *d* show when the water was withdrawn, and *e* shows curve produced by sudden thunder shower.

These experiments showed that there was a positive connection between changes in the soil temperature and changes in the movement of water in the soil. Since the water left the well and entered the soil with a lowering of the temperature, it follows that the observed changes could not be the result of a change in the volume of the cylinder due to shrinkage and expansion, for the movements of the

water were in the opposite direction from what a change in volume would have produced.

The quantitative relation existing between the movement of the water in the soil and the change in temperature is expressed below.

Date.	Mean temperature of soil.		Amount of change in temperature.		Amount of change in water.	
	A. M.	P. M.	A. M. to P. M.	P. M. to A. M.	A. M. to P. M.	P. M. to A. M.
	° *C.*	° *C.*	° *C.*	° *C.*	*Inches.*	*Inches.*
July 7	19.4	26.3	+ 6.9	....	+ 2	....
July 7-8	26.3	19.4	....	— 6.9	....	— 2
July 8	19.4	23.5	+ 4.1	....	+ 1.8	....
July 8-9	23.5	20.7	....	— 2.8	....	— 1.84
Mean	....	....	5.175° *C.*		1.91 *in.*	

Here we have a mean change in water-level amounting to .369 inch for each degree C.

Taking the period from June 6 to 9 we have—as below—

Date.	Mean temperature of soil.		Amount of change in temperature.		Amount of change in water.	
	A. M.	P. M.	A. M. to P. M.	P. M. to A. M.	A. M. to P. M.	P. M. to A. M.
	° *C.*	° *C.*	° *C.*	° *C.*	*Inches.*	*Inches.*
June 6	17.3	22.7	+ 5.4	....	+ 1.22	....
June 6-7	22.7	18.3	....	— 4.4	....	— 1.17
June 7	18.3	20.5	+ 2.2	....	+ .72	....
June 7-8	20.5	17.4	....	— 3.1	....	— .87
June 8	17.4	20.5	+ 3.1	....	+ .87	....
June 8-9	20.5	17.3	....	— 3.2	....	— 1.1
Mean	....	....	3.57° *C.*		.99 *in.*	

In this case we have a mean change in the water-level of .276 inch for each degree C. The cavity into which the water percolated and from which it was again withdrawn with each change of temperature had a diameter of 5 inches, so that the amount of water which left the soil and entered the well was about 6 cubic inches for each degree C. I suppose it was also true that the non-capillary spaces in the soil above the water level in the well were also filled to a certain depth and emptied again, so that the total movement of water in the circle of soil 30 inches in diameter was something more than the 6 cubic inches stated above.

In another cylinder, 10 feet long and 1 foot in diameter, standing in a large silt well 6 feet deep and 4 feet in diameter, the water rose and fell daily between July 15 and 18 an average of 3.33 inches as measured by the change of level of water in a glass tube communicating with the bottom of the cylinder. And, in this case, I suppose the surface of the ground-water in the cylinder rose and fell each day through the mean distance stated. How great the diurnal change

of the soil-temperature may have been in the cylinder is not known, but as the cylinder stood below the level of the ground surface in a cavity into which water from the drains was discharging, I suppose that the diurnal range in the cylinder could not have exceeded 2° or 3° C. below the surface of the ground.

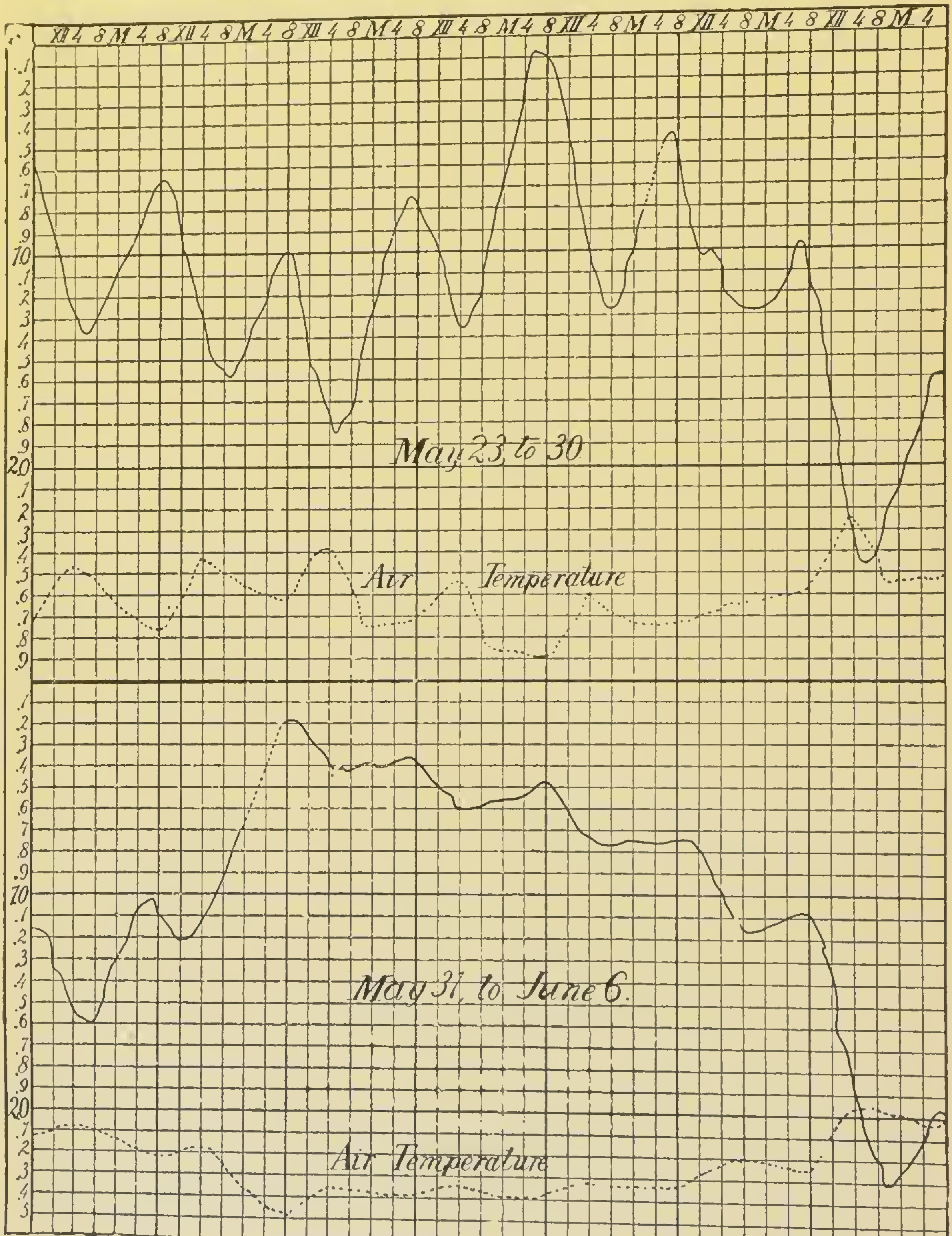

FIG. 33. Diurnal changes in level of water in the well in the cylinder from May 23 to June 6, 1892, and the corresponding air temperatures for the same period.

In Fig. 33 the changes in the level of the water in the well in the cylinder are plotted for two weeks, and side by side with these is plotted the tri-daily air temperature as observed at Washburn Observa-

tory. Here it will be seen that there is apparently no evidence of barometric fluctuations, but a close agreement with the temperature curve.

There is, therefore, in my judgment, no ground for reasonable doubt but that these diurnal oscillations of the water level in the two cylinders were due to an oscillation in the intensity of the capillary power manifested in the soil contained.

To ascertain whether temperature changes in the soil of the field produce a manifest movement of the soil water, it is required to show, in the first place, diurnal oscillations which are evidently not barometric, and second, that the turning points of these curves are on the turning points of the soil temperature in the zone in which the movement of the water takes place. That there are diurnal oscillations evidently not related to any of the observed barometric changes of pressure, has been pointed out, and it remains to show that these do or do not fall into unison with the diurnal temperature curve.

My first effort in this direction was to ascertain whether any probable change of temperature in the wall of the wells was capable of producing the amount of movement observed, and to do this an apparatus was constructed and set in the soil, consisting of a double walled cylinder taking the place of the tile in the well, and a current of warm water, having a temperature of from 70° to 90° F., was kept circulating through it during three consecutive hours on three different days. One of the one-day recording instruments was used to register the fluctuations in the level of the water in the well. There was in no one of these trials any change in the curve which appeared to have any connection with the time of beginning or closing of the experiments, and yet the changes in the temperature of the walls of the well must have been greater than the diurnal range due to atmospheric changes of temperature. I then buried bodily a thermograph, first at a depth of 5 feet and then at a depth of 18 inches. The degree lines in this instrument were too close to detect more than the slightest diurnal change at the greater depth, but at 18 inches the diurnal range was appreciable but could not be measured very accurately, and as the instrument in its box occupied a space of 9 inches, the temperature change recorded could not be located at any definite plane. I then constructed a thermometer, in the form repre-

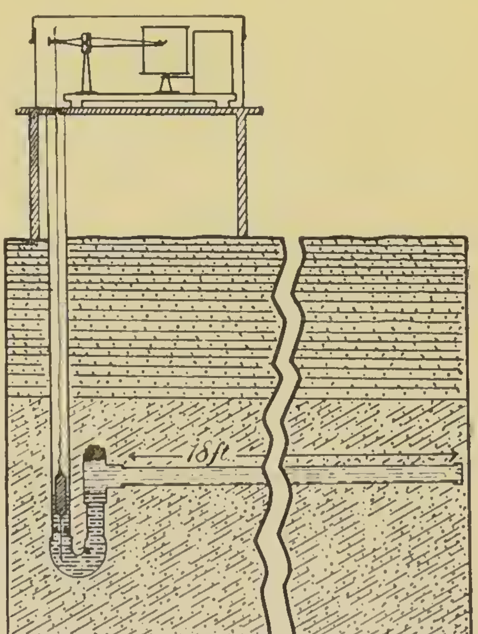

FIG. 34. Construction of new form of self-recording soil thermometer.

sented in Fig. 34, out of 1¼ inch gas pipe 18 feet long, and filled it with alcohol, which was made to act upon a plug of mercury in the bend of the tube, the latter moving a float which was attached to one of the recording instruments used on the wells. Only an approximate calibration of this instrument was attempted, and this was done by placing a soil thermometer in contact with the center of the tube in the soil and keeping a record of its changes as checks upon the other.

The curve produced by this instrument, placed 18 inches below the surface, and that of a thermograph sheltered at a height of one foot above the ground at the place, giving the air temperatures for the same period, are shown in Fig. 35. Here it will be seen that the soil at 18 inches below the surface is subject to a diurnal oscillation amounting to about 1° F., and that the lowest temperature in the soil occurs, at this level, a little after noon and the highest a little after midnight.

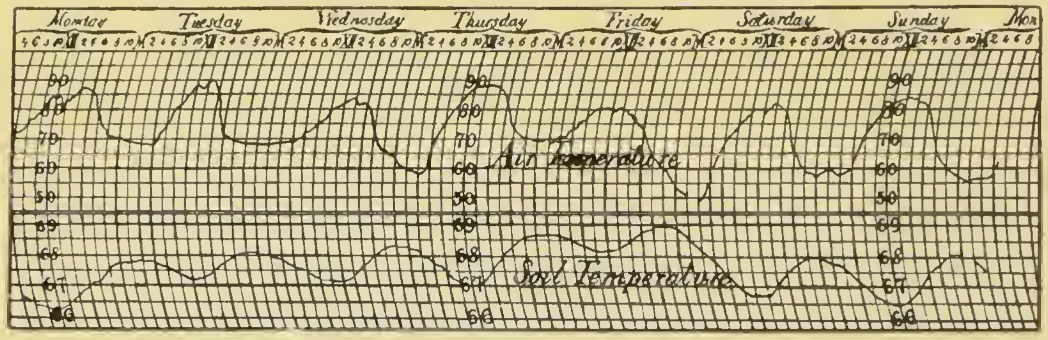

FIG. 35. Diurnal changes in soil temperature 18 inches below the surface, and corresponding air temperature for the same period.

We have no observations, as yet, which definitely settle from what level the water, which produces the rise in the well, comes, but I know no reason for supposing that the chief part comes from above the 18-inch level. If the water comes from below the 18-inch level the temperature changes which effect its movement should be expected to lag still more behind those of the air and so bring the highest temperature, not a little after midnight, but at some later interval. Referring to the figures showing the diurnal oscillations in question, it will be seen that the lowest points in the curves, which represent the highest water in the well, and which correspond to the warm epochs in the soil-cylinder referred to, occur at from 6 to 8 in the morning and, as the level of the water in the wells and that which discharges into the drain is more that twice the depth of the soil thermometer below the surface, there appears no great improbability that the lagging of the temperature wave is entirely sufficient to cause the percolation into the wells to occur at the time at which the curves show that it does take place.

The reason for the absence of oscillations during the spring and early summer due to changes in the soil temperature may not at first

be apparent, nor can one be assigned with any degree of assurance until we have obtained satisfactory continuous records of soil temperature at various depths below the surface. Still, observations do show that the temperature does progress downward slowly, and while the surface soil is so full of water, which is being evaporated from the surface rapidly, there would be relatively less energy left daily for transmission downward. Besides this, the zone of soil in which diurnal oscillations are appreciable, we have reason to expect is progressively increasing during the whole season of increasing temperature, and future continuous records may show that below even a very shallow depth there are, early in the summer, no measurable oscillations of this character.

There is another possible cause of increasing diurnal oscillations later in the season which does not exist in the spring. I refer to the extension and occupancy of the soil by the roots of growing vegetation. Since large volumes of water are carried to the surface in increasing quantities as the season advances, and since sap from the stems and leaves bathed in the warm air is carried downward into the ground to feed the roots, we may expect a certain quantity of heat to be transported below the surface and to considerable depths in this manner, and this would have an increasing effectiveness later in the season as the water is withdrawn from the soil, for such withdrawal must very materially diminish the mean specific heat of the soil, thus allowing the same number of heat units to produce a greater change in temperature.

EFFECT OF INCREASING SOIL TEMPERATURE ON THE GENERAL HEIGHT OF THE GROUND-WATER SURFACE.

Since the water-holding power of soil is decreased by an increase of temperature it follows that the seasonal rise of temperature in the ground must have the effect of increasing the rate of percolation and of enabling some water to reach the ground-water level which, during the earlier season, would be retained in the soil by capillary action. This effect, therefore, must tend to hold the level of ground-water above what it would otherwise occupy. The same cause would also tend to decrease the per cent. of water in the soil below the surface and cause it to appear to be drying out by capillary action upward, when in reality the drying was the result of percolation downward, due to a rise in the soil temperature.

INFLUENCE OF CHANGES IN SOIL TEMPERATURE ON UNDERGROUND DRAINAGE.

If it is admitted that an increase in soil temperature decreases the water-holding power of the soil, it should be expected that under suitable conditions drains should show a diurnal variation in the

rate of discharge, due to diurnal changes of temperature. The curve produced by the drain gauge, which is shown in the figure, with those of the wells exhibiting the marked diurnal oscillations, appears to be in perfect accord with them so far as the diurnal oscillations are concerned, and hence indicates that there are or may be diurnal changes in the rate of flow of water from the ground, due to temperature changes.

During some laboratory studies conducted at this station, in which the writer attempted to ascertain whether the presence or absence of salts influenced the rate of flow of water through soil, he found that the apparatus was so extremely sensitive to temperature changes that no concordant results could be obtained until the whole apparatus was put under complete control so far as changes in temperature were concerned. To illustrate this influence the following results may be cited: Starting with the apparatus filled with a coarse sand and at a temperature of 9.01° C., the flow = 6.153 grams per minute; at 9.23° C., the flow = 6.27 grams per minute; at 9.38° C., the flow = 6.384 grams per minute; at 12.6° C., the flow = 7.046 grams per minute; at 23.8° C., the flow = 9.014 grams per minute; at 32.46° C., the flow = 10.54 grams per minute.

While it is likely that a part of the increase in the rate of flow through this sand was due to the fact that the coefficient of expansion of the walls of the apparatus and that of the sand were not the same, yet the differences in the rate are too large to be accounted for completely in this manner.

In case it is true that changes in the temperature of soil do affect the rate of flow of water through it, it should be expected that the configuration of the general ground-water surface would change as a consequence of this temperature influence, for under the lower grounds, where the summer temperature penetrates more quickly to the zone in which the water is flowing toward drainage outlets, the resistance to flow would be decreased and the surface of ground-water would fall more rapidly as a consequence than it would under the higher and colder ground.

Then, again, under the reverse conditions of winter, when the low lands are colder at the level of ground-water than under the higher land, the resistance to flow would be increased and the relatively more rapid drainage from the higher lands would tend to raise the water surface under the colder low lands above the normal, and hence to develop, toward spring, an attitude of the ground-water surface approaching more nearly to horizontality than is normal to the summer season.

We have shown that the diurnal variation in the temperature of the soil at a depth of 18 inches below the surface is, at the date of writing, only about 1° F., and that it is probably less than this at the

depths of the wells and drains, and yet the continuous records obtained appear to show that such small changes of temperature are effective in modifying the rate of discharge of water into the drains as well as upon the height of water in the non-capillary spaces of the soil. Now, if the movements of water through the soil are thus sensitive to temperature changes it follows that in two countries where the mean soil temperatures vary to a considerable extent, the effectiveness, capacity, proper depth, and distance apart of tile drains may be found to materially differ.

TEMPERATURE TIDE OF THE GROUND-WATER SURFACE.

It follows, from the observations here recorded, that in all places where the diurnal oscillations of soil temperature reach the ground-water this surface is by it subjected to an ebb and flow vertically over the surfaces of the soil grains, which reaches upward possibly even through the zone of soil containing only hygroscopic moisture; for if the thickness of the film of water which can be borne by the soil grains varies with the temperature, there may be a progressive thinning and thickening of this film as the temperature rises and falls, and, if this is true, the soil grains are subjected to an exchange of water upon their surfaces throughout a deep zone, which must influence greatly those disintegration processes which contribute so much to the fertility of soils and to the leaching of them. Even if this ebb and flow is confined to a zone extending but a foot above the level where the non-capillary spaces in the soil remain full, the sum total of its effects must still be very great.

SEISMIC OSCILLATIONS OF THE GROUND-WATER SURFACE.

One of the surprising observations made during this study is that a heavily loaded moving train has the power of disturbing the level of water in the non-capillary spaces of the soil, but in just what man-

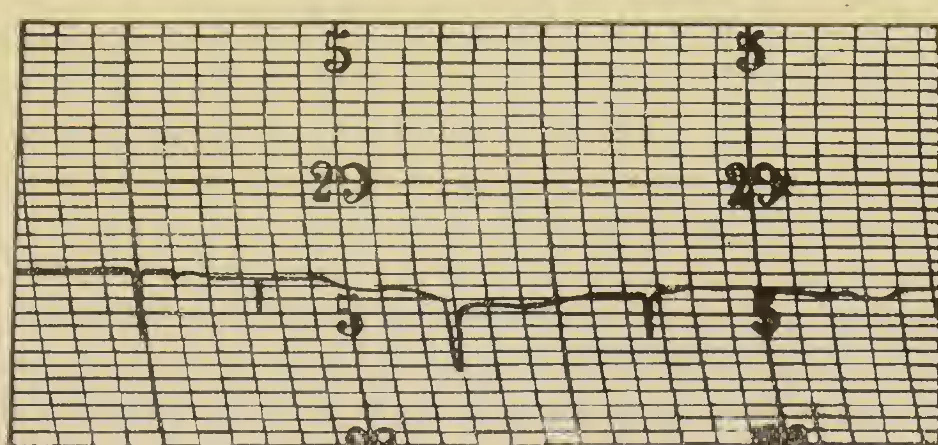

FIG. 36. Changes in level of water in well produced by moving train.

ner this is brought about is not easy to see. The observed facts are these: While the self-registering instrument was upon well 48 it was

observed that there were frequent records of sharp, short period curves shown upon the sheet, which at first were supposed to be the result of accidental jars which the instrument sustained; but the frequency of their occurrence, and the fact that they were always dependent from the other curve, led to a closer scrutiny of them and their final association with the movement of trains past the well. On the eight-day instrument these fluctuations were shown as single dashes, but with the one-day form the curve was open and having the character shown in the tracing, Fig. 36. The well in which these disturbances occur is situated about 140 feet from the railroad track, and has a depth of 40 feet. It is tubed up with 6-inch iron pipe to the sandstone, 37 feet below the surface, and the water has a mean depth of about 20 feet in it.

The strongest rises in the level of the water are produced by the heavily loaded trains which move rather slowly. A single engine has never been observed to leave a record, and the rapidly moving passenger trains produce only a slight movement, or none at all, which is recorded by the instrument. The figure shows the curve to be produced by a rapid but gradual rise of the water, which is followed by only a slightly less rapid fall again to the normal level, there being nothing oscillatory in character indicated by any of the tracings nor observable to the eye when watching the pen while in motion. The downward movement of the pen usually begins when the engine has passed the well by four or five lengths, and when the pen is watched it may be seen to start and to descend quite gradually, occupying some seconds in the descent. The actual amplitude is one-third of that shown in the cut, which represents about the average occurrences, and these disturbances are not peculiarities of the present season when the ground-water surface occupies a higher plane than it has during the three years past, for the records of last year, which were procured with the improvised instrument to which reference has been made, bear evidence of the same disturbances produced then.

The manner in which a train moving across the ground-water surface lying seventeen to twenty feet below can effect such changes as the instruments have recorded is not at once apparent, especially when it is observed that the site of the records is 140 feet distant from the railroad track. The first explanation which suggests itself is that the short period shocks which the earth sustains in the transit of the train are transformed into a wave of long period which is propagated radially from the center of the disturbance and, reaching the well in its course, produces the record there obtained; but such an explanation appears to be rendered inadmissible because there is one single rise and fall, with no trace whatever in the curve of a repetition, as a true wave implies. A more probable hypothesis perhaps is that the mass of the train in its transit by the well depresses the

earth bodily, causing it to sink into the ground-water more deeply and thus displace it laterally, causing it to rise under the surrounding area; but if this is true, and the displacement of the water has occurred equally in all directions, a rise of one-tenth of an inch at the well, 140 feet distant, means a downward displacement at the track amounting to something more than this, apparently twice that amount at least.

So far as the character of the curve and the method of recording it are concerned it would be equally admissible to suppose that the ground, as far away as the location of the instrument, was bodily depressed so that the recording apparatus moved downward, rather than that the surface of the water in the well moved upward, in producing the curve; but on this hypothesis the amount of earth moved seems enormously great when compared with the inertia of the train which produced the rise of water in the well. Again, it may be urged that the movement at the well which produced the record was the result of an upward thrust of the ground-water surface and a downthrow of the soil in the same place, so that the total movement in either case may not have exceeded .05 of an inch.

As still another alternative, it may be urged, that, either by compression of the zone of capillarily saturated soil lying just above the ground-water surface, or by its frequent recoils from the shocks imparted by the moving train, some of the capillary water is forced out of the soil and made to raise the mean level of the ground-water, thus augmenting the head so as to cause the water to rise in the well. But to raise a float one-tenth of an inch at a distance of 140 feet implies a dislodgement of capillary water and an augmentation of head seemingly too large to be produced by the most heavily loaded train.

Since such changes as result from the movement of a train over the ground affect the level of the water in it to such an extent as to be susceptible of measurement in the manner described, we may, perhaps, expect to find that the ground-water is sensitive to seismic disturbances and that the method here used, or a modification of it, is capable of rendering valuable information in volcanic districts regarding earth-tremors due to such causes. Indeed, the extreme complexity of some of the curves obtained here, and more especially of those obtained at Whitewater, of which tracings are given, implies, either that the barometric oscillations are much more frequent and of wider amplitude than we are accustomed to think, or else that the earth here is subject to tremors which may be recorded by fluctuations in the changes of level in the ground-water surface.

THE MECHANICAL ACTION OF BAROMETRIC CHANGES IN PRODUCING FLUCTUATIONS IN THE LEVEL AND DRAINAGE OF GROUND-WATER.

The evidence now at hand is insufficient to show, in a satisfactory

and conclusive manner, just how changes in atmospheric pressure produce those changes in the level of the water in wells and in the rate of flow from the ground which have been shown to be closely associated with them. Unless some overshadowing influence is in operation at the same time, a rise in the barometer is very nearly coincident in time with a fall of the water in wells and with a diminished rate of discharge of water from the ground, and *vice versa.*

There are two radically different methods of action, by either of which we may suppose the phenomena in question are brought about through changes in atmospheric pressure. In the first place, it may be supposed that the general level of the ground-water surface is depressed or elevated bodily, as the case may be, by barometric changes, the loading of air upon a region depressing the ground-water surface of that region and the unloading of it permitting the level to be partly or wholly restored again. In the second place, it may be supposed that, through an unequal permeability of the soil above standing water in the ground, the changes in atmospheric pressure are more quickly felt by the water surface at some points than at others, and, as a consequence, a rising barometer will cause the water to be depressed in wells and in open soils, the water rising into both the capillary and non-capillary spaces of the adjacent less permeable areas, while a reduced air pressure would permit the confined air in the soil of the more impermeable regions to react and force the water into wells and drains, thus producing the phenomena associated with a falling barometer.

If a high barometric area develops over the west Atlantic Ocean while a low area has formed upon the eastern portion, maintaining a difference of pressure of one inch, the ocean surface, as a result of this unequal loading, will be deformed to the extent of 1.13 foot, the water-level on the west falling, while that upon the east rises through one-half of this distance; so if we suppose a continental ground-water surface in a state of drainage equilibrium to be similarly circumstanced, its surface would be, in a like manner, deformed, and as a result of this deformation, the water would stand higher in the wells and discharge more rapidly from the springs and drains of the low-pressure area while the converse would be true under the high area.

*If Mr. G. H. Darwin is right in his estimate, that if the barometer rises an inch over an area like Australia the load is sufficient to sink the continent two or three inches, and that the tides, which, twice a day, load the shores of the Atlantic, may cause the land to rise and fall as much as five inches, there appears no physical reason why, the ground-water surface being more mobile than the rigid earth, and at the same time capable of moving through its interstices, should not

* Nature, Vol. XVI, page 367.

suffer a deformation greater than that of the land itself when subjected to a similar load. If a horizontal canal be conceived to span a distance of two thousand miles and to lie above the general drainage plane so that water might discharge from opposite ends through gates of equal capacity, it is evident that, were a low barometric area to rest upon one end, the water would discharge from that gate at a rate exceeding the average while at the opposite gate the rate of discharge would be less than the mean. In a like manner, if it is possible for atmospheric changes to depress or raise the ground-water surface in the vicinity of a system of tile drains, the water would flow more or less rapidly from this system according as the region was under the influence of a high or low barometric pressure.

It has been shown on a preceding page that the mean fall of the ground-water surface during times of rising barometer, as estimated by changes of level in wells, was .224 inch daily, while during times of falling barometer the mean fall was only .001 inch per day. Such a relation as this should be expected to exist if barometric changes are capable of affecting the general level of ground-water in the manner here under consideration. Then, again, in the case of the well in the galvanized iron cylinder, Fig. 31, in which the influence of temperature changes was shown, but which was constructed for the purpose of ascertaining whether or not the barometric changes were thus local in their effects, the curves nowhere show changes which can be ascribed to barometric influence, and this is what should be expected if the fluctuations are due to oscillations of the general ground-water surface. It is evident, however, that neither of these facts can be cited as lending much support to the view.

Turning now to the second hypothesis, the following conditions furnish the foundation for it: The condensation capacity of water for air varies with the pressure to which it is subjected, and, this being true, atmospheric changes are capable of affecting the volume of free air in the soil. It has been shown elsewhere in this paper that saturated and nearly saturated soils, especially those of fine texture, are nearly or quite impermeable to air under atmospheric changes of .1 of an inch. The capillarily saturated soils under field conditions possess both capillary and non-capillary spaces which contain air.

Under these conditions it may be assumed that when an area of low barometer passes upon a given district the equilibrium between the confined gases and capillary tension is destroyed, and by the expansion of the air escaping from the water and that which exists in the capillary and non-capillary spaces of the soil above the ground-water level capillary water is forced out into the wells and into drainage channels, and thus increases the underground drainage for the time and the height of water in wells and in soils to which the

air has free access. Then, when the barometric conditions are reversed, the permanent rarefaction which the soil-air has sustained through the withdrawal of water, and air as well, from the interstices of the more impermeable soil permits the increased barometric pressure to force the water from the well back into the passageways from which it came and thus lower the water-level in the well; then, too, in the case of springs and drains, if the water is flowing from more or less impermeable beds an increase of pressure would increase the resistance against which the water was flowing from the soil, while a decrease of pressure would amount to the same thing as giving the water a steeper gradient.

This hypothesis appears much more applicable to the very short period fluctuation, which the records so often show, than it does to those which are more gradual and involve the movement of so much larger volumes of water, as in the case of the spring at Whitewater, which continued to flow under an increased head for days in succession with a falling barometer, producing a curve very nearly concentric with that of the barometer as far distant as Madison. It should be stated also in this connection that the barometric change of level in wells bears no definite relation to the diameter of the well into which the water percolates, the rise being very nearly or quite as great in a well 4 feet in diameter as it is in one 5 inches in diameter, and yet it would seem that, if the water is drained out of the soil locally, the larger the well the slower its level should change. This difficulty may perhaps be satisfactorily met by supposing that the positive or negative gaseous tension reacts vertically chiefly upon the general ground-water surface, causing it to rise and fall in a considerable measure bodily.

CAUSE OF TEMPERATURE OSCILLATIONS IN THE LEVEL OF GROUND WATER.

The amount of water which has been shown to leave the capillary spaces of the soil with an increase of temperature, and to return to them again when the changes are reversed, is so great as to make it difficult to understand how a simple diminution of the surface tension of the soil-water is capable of producing the whole movement, and has led the writer to suspect that possibly the expansion of the soil air contained in the capillary spaces of the soil, which is very nearly saturated, may, by its change of volume with change of temperature, account for a portion of the changes observed.

INSTANTANEOUS PERCOLATION AFTER RAINS.

It has been mentioned, in referring to the laboratory experiment relating to the distribution of capillary water in long columns of soil, that upon adding water to a column of coarse saturated sand, but which had ceased to percolate, the water began flowing again as

soon as more was added to the surface. In this case the water which percolated at first was not that added to the surface, as was proven by

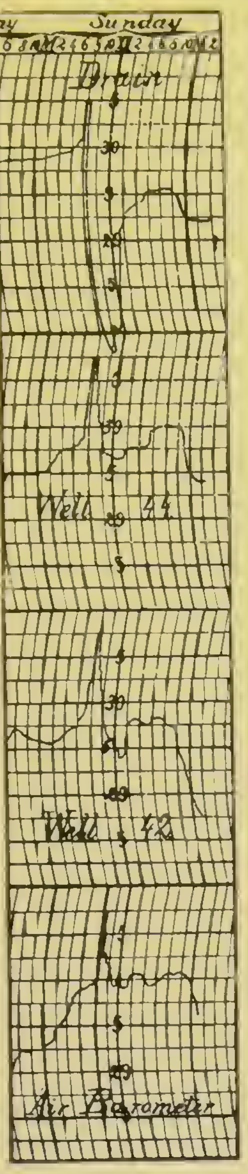

Fig. 37. Curves due to instantaneous percolations after rains.

the fact that in a short time the percolation ceased but only to begin again several hours later. The same fact I have observed in the field, and in Fig. 37 are produced the curves obtained with three of the self-recording instruments at one of these times; two of them on wells and one upon a drain. On the morning of July 24 a sudden shower came from the north of west, and just as the black clouds were approaching, apparently about 20° above the horizon, the barometer began suddenly to rise and continued to do so until a few minutes after the rain began, when it fell almost as suddenly to .05 of an inch below the starting point. On going to the wells and drain in less than 10 minutes after the shower of 15 minutes' duration had ceased, I found that the water had raised and was flowing so much more rapidly from the drain as to oblige the pen to be reset. The curve from the drain shows very conclusively that an increase in the discharge had occurred which persisted after the barometric change had passed.

These cases of sudden percolation I believe to be due to hydrostatic pressure which the water, falling upon the surface so rapidly as to close the air passages, exerted through the soil air upon the ground-water below.

PERCOLATION THROUGH FROZEN GROUND.

There appears to be a quite general impression that while the ground is frozen there can be little or no percolation through it. This is so far from being true that, during three consecutive winters, at times of sudden thaws or winter rains which melted considerable snow, the system of drains on the Experiment Station farm has discharged water so rapidly into the big silt well, No. 25, Fig. 3, that a 6-inch tile drain 560 feet long was only able to carry away the water brought to it when it had a fall of over 2 feet and a head in the well of nearly 4 feet. Not only has the water been observed to find its way into the drains through the frozen ground, but also into the shallow wells. During these times the water appears to find its way into the ground through shrinkage cracks, through perforations made by earth worms, and does so without apparently contributing very much to the surface 3 feet of soil. These facts are significant in the bearing they have upon the practice, now coming to

be so general, of spreading farmyard manure upon the field during the winter. I would not here urge that these observations should disparage the practice, but that the matter is one which merits careful consideration in the study of the advantages of winter manuring.

SOME DIRECTIONS IN WHICH FURTHER STUDY IS NEEDED.

It should be at once apparent, in a subject possessing the extreme complexity of the one under consideration and presenting so many aspects of economic and scientific interest as does the movement of rain after it has penetrated the ground, that the observations herein presented can only be regarded as of the nature of a preliminary reconnoissance of but a small portion of a field in which our exact knowledge is relatively very limited.

A careful and detailed study of the movements of ground-water ought to supply very important knowledge bearing upon the contamination of drinking waters and the spreading of certain classes of contagious diseases, and thus help to place the water supply for both urban and rural purposes under better sanitary conditions.

Every advance which is made toward the increase of yield per acre necessarily means an increased demand for water, so that market gardeners even in Wisconsin and Illinois, where both the annual and summer rainfall is relatively large, are turning their attention toward providing suitable means for irrigation; and a rapid and economical advance in this direction demands a much more thorough knowledge of the movements of underground water than we at present possess.

In the utilization of natural subirrigation, to which reference has been made, and in the reclaiming of swamp lands for agricultural purposes, which must be of growing importance in the immediate future, there is imminent need for new knowledge in the same direction.

Before we can understand the full significance and extent of the movements of underground water, it will be necessary to have synchronous observations covering, not only considerable intervals of time, but also extended areas as well, and valuable contributions to our knowledge should be expected if improved forms of self-registering apparatus for recording the changes in the level of ground-water were to be set up at many meteorological and experiment stations; and since the soil-water has been shown to be so susceptible to movements resulting from small barometric and temperature changes, there should be forms of self-recording soil-thermometers more sensitive than any now available, and barographs which are capable of recording much smaller changes of pressure than most existing instruments do. It may be that a barograph constructed on the principle of the air barometer described in Fig. 23, but using a fixed oil instead of water, filling the chamber with chemically dry air and burying the

whole more deeply in the ground, where the diurnal changes of temperature would always be very small, would answer the needs of such a study.

If the movements of ground water generally even approximate those which the observations here recorded appear to indicate, a fuller understanding of them must shed much light upon those metasomatic changes which are of such great importance in geologic processes and in the origin and formation of metalliferous deposits.

Then again, if tidal fluctuations do really exist in the ground-water, as Mr. Roberts has affirmed, and if it is sensitive to seismic disturbances, as the observations here recorded in regard to the moving train suggest, a study of the movements of ground water may be expected to contribute much toward an understanding of the nature, extent, and effects of the movements of the solid portions of the earth, whether they are due to stresses originating in extra-terrestrial causes or geologic or meteorologic shiftings of load upon the earth's surface.

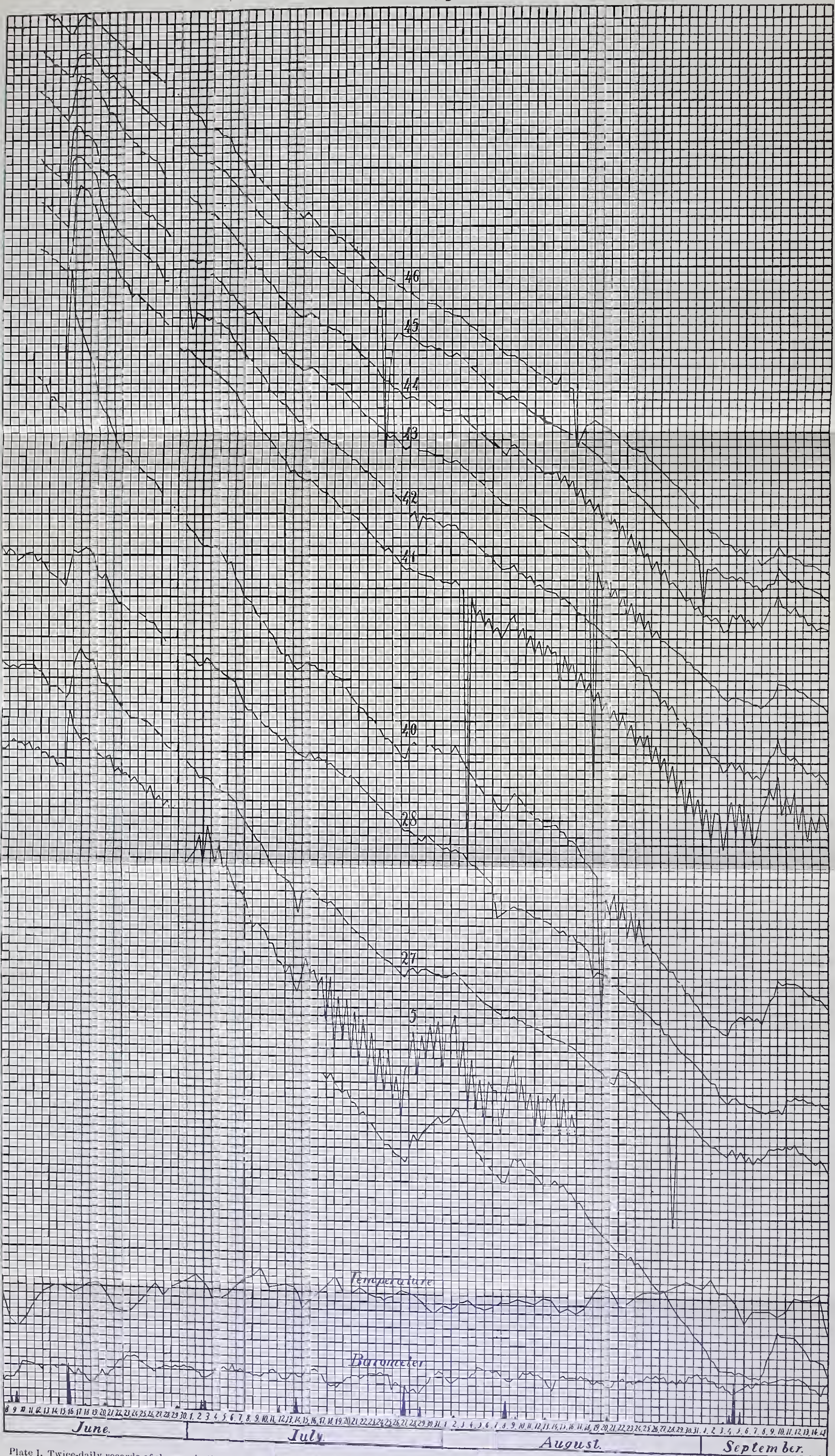

Plate I. Twice-daily records of changes in the level of the ground-water surface from June 8 to September 17, 1889. P. M. measures fall on the lines and A. M. measures between them. The distance between horizontal lines represent .2 inch.

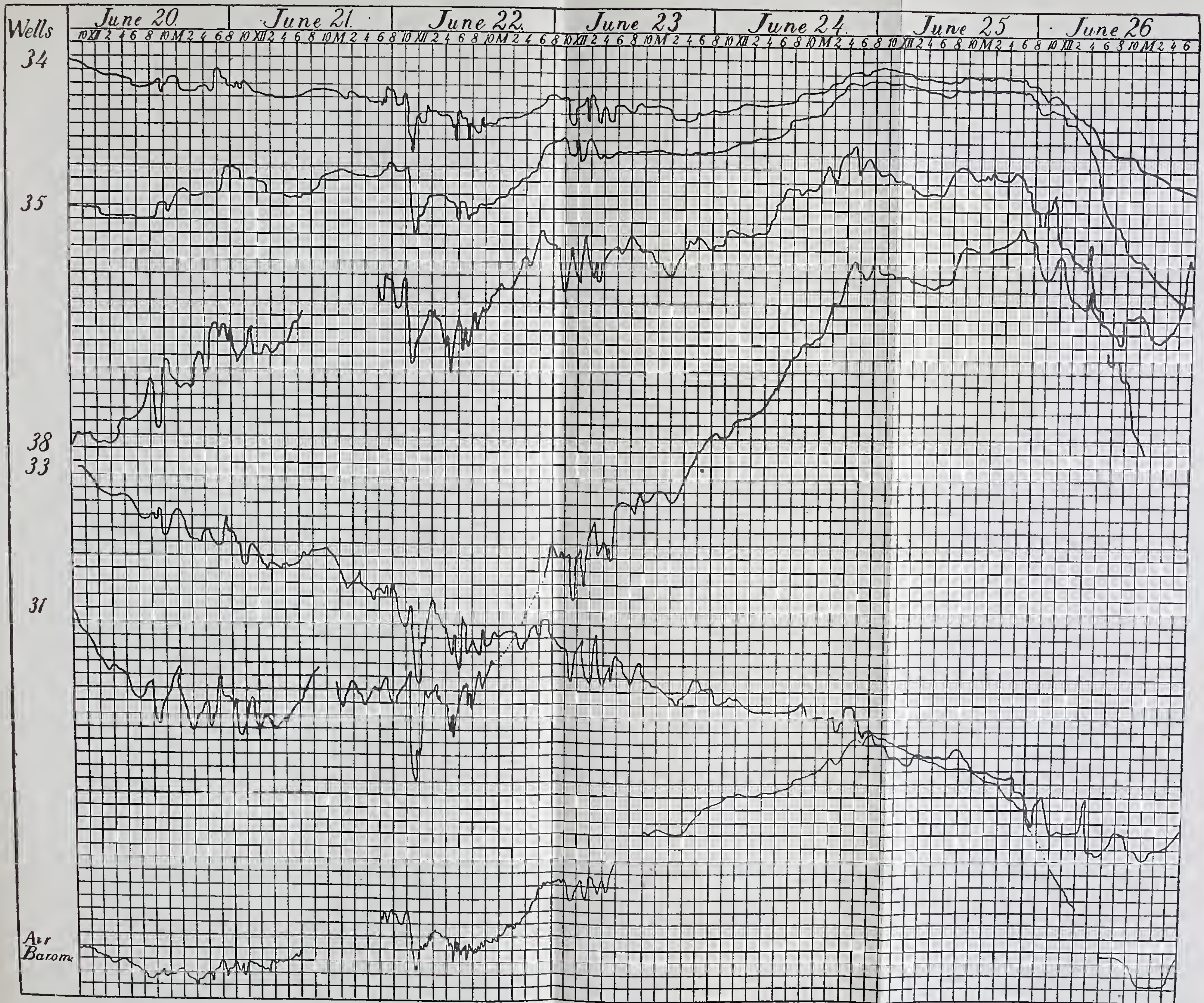

Plate II. Synchronous fluctuations in wells and air barometer from June 20 to 26, 1892.

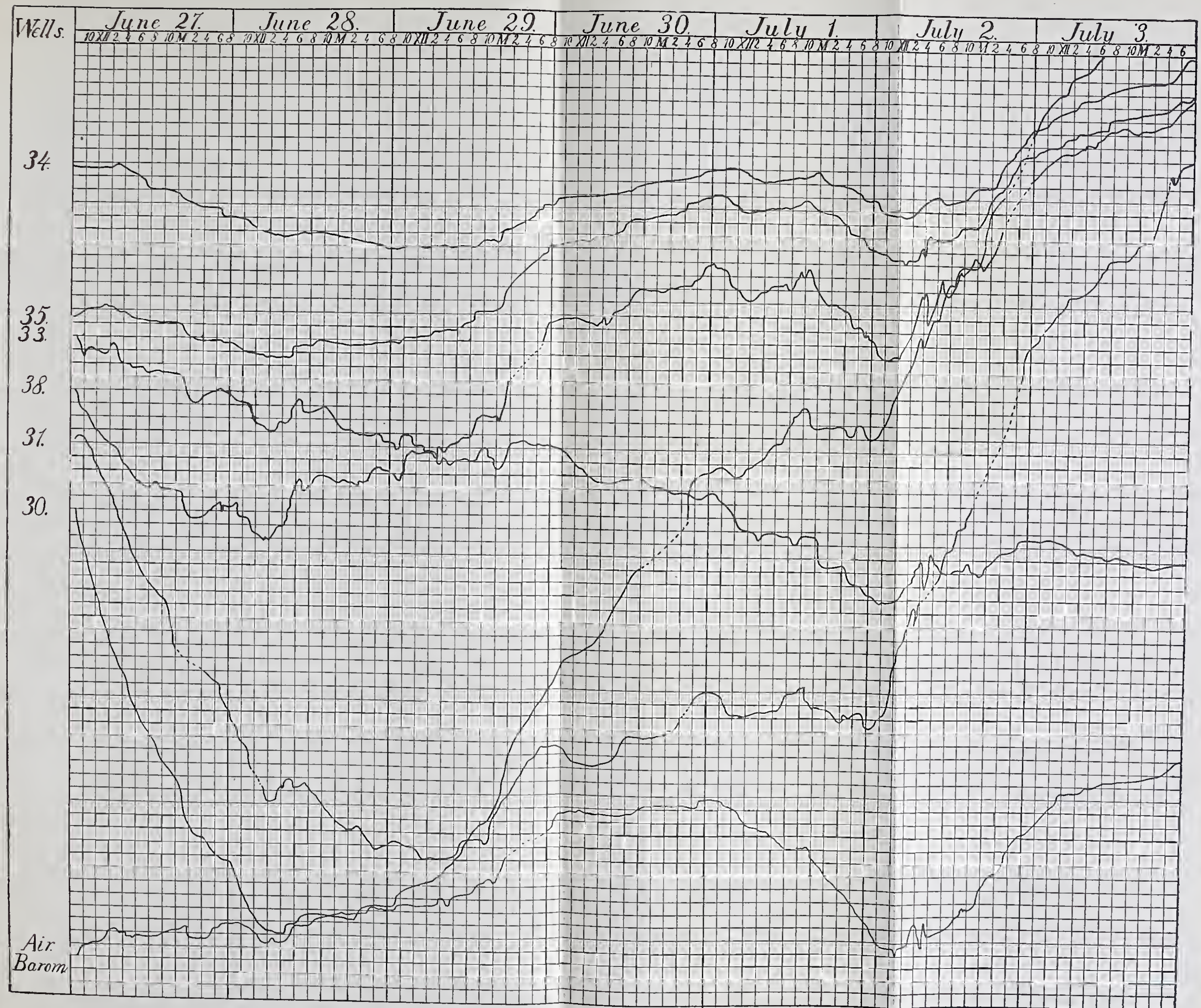

Plate III. Synchronous fluctuations in wells and air barometer from June 27 to July 3, 1892.

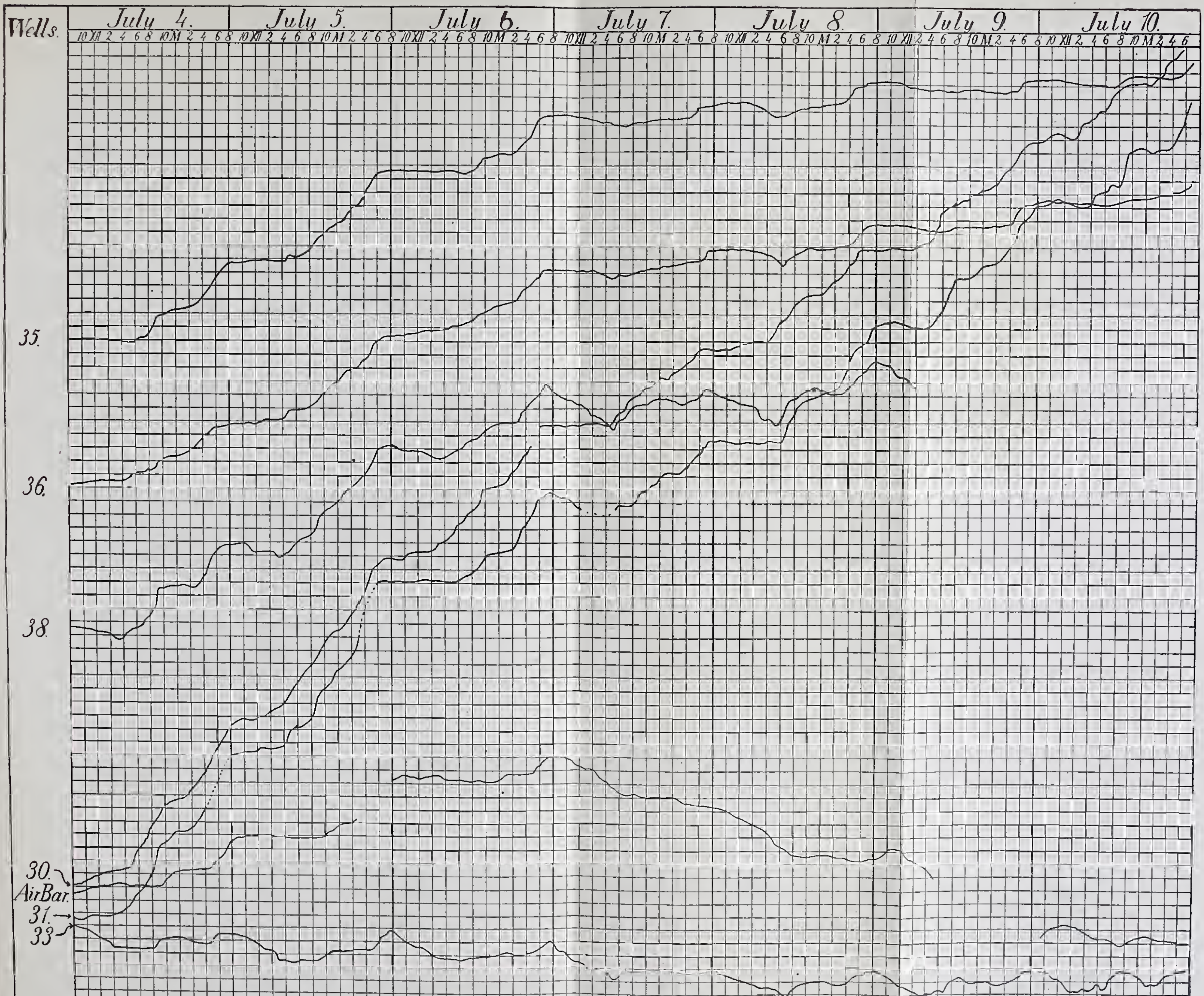

Plate IV. Synchronous fluctuations in wells and air barometer from July 4 to 10, 1892.

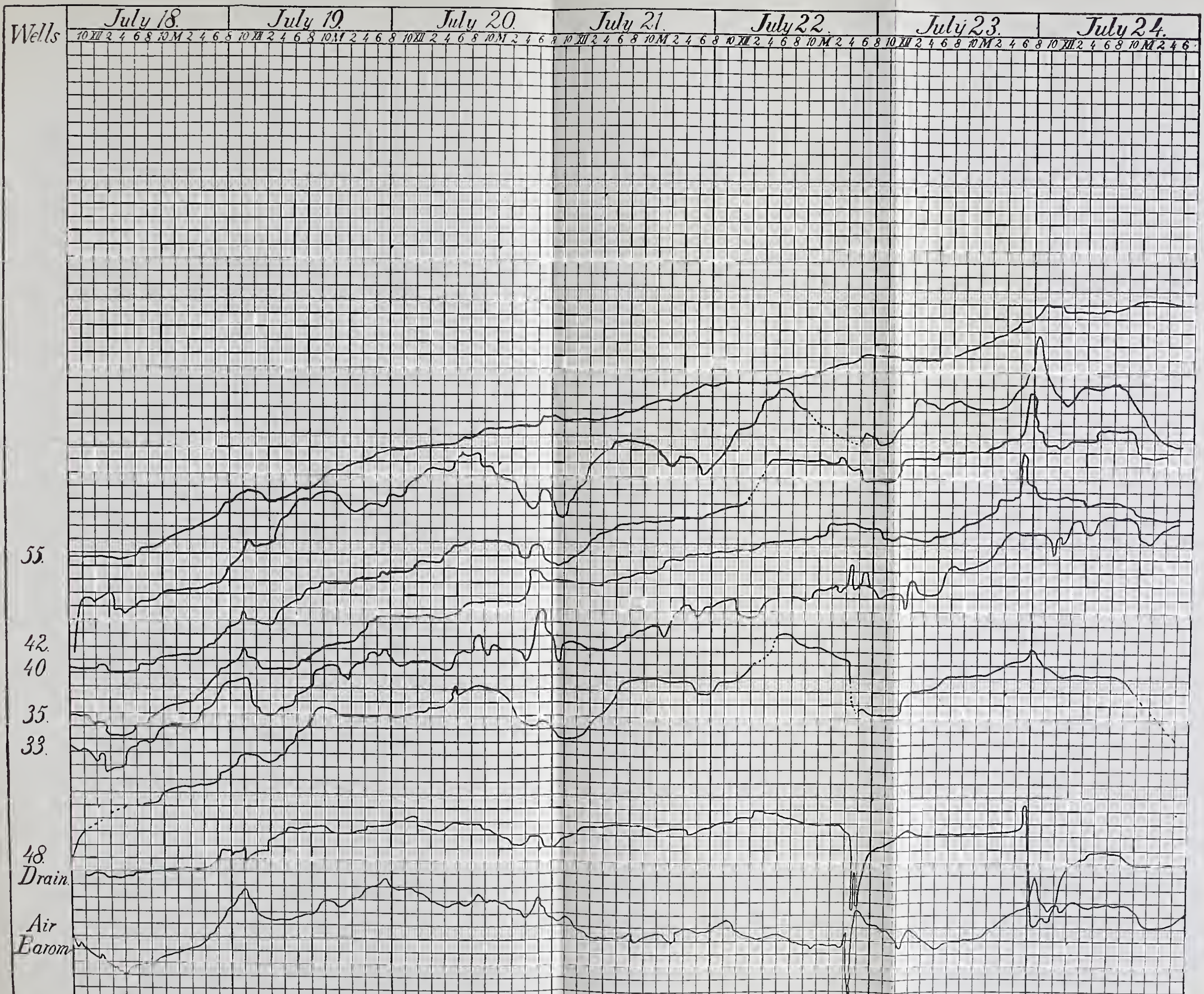

Plate V. Synchronous fluctuations in wells, drain, and air barometer from July 18 to 24, 1892.

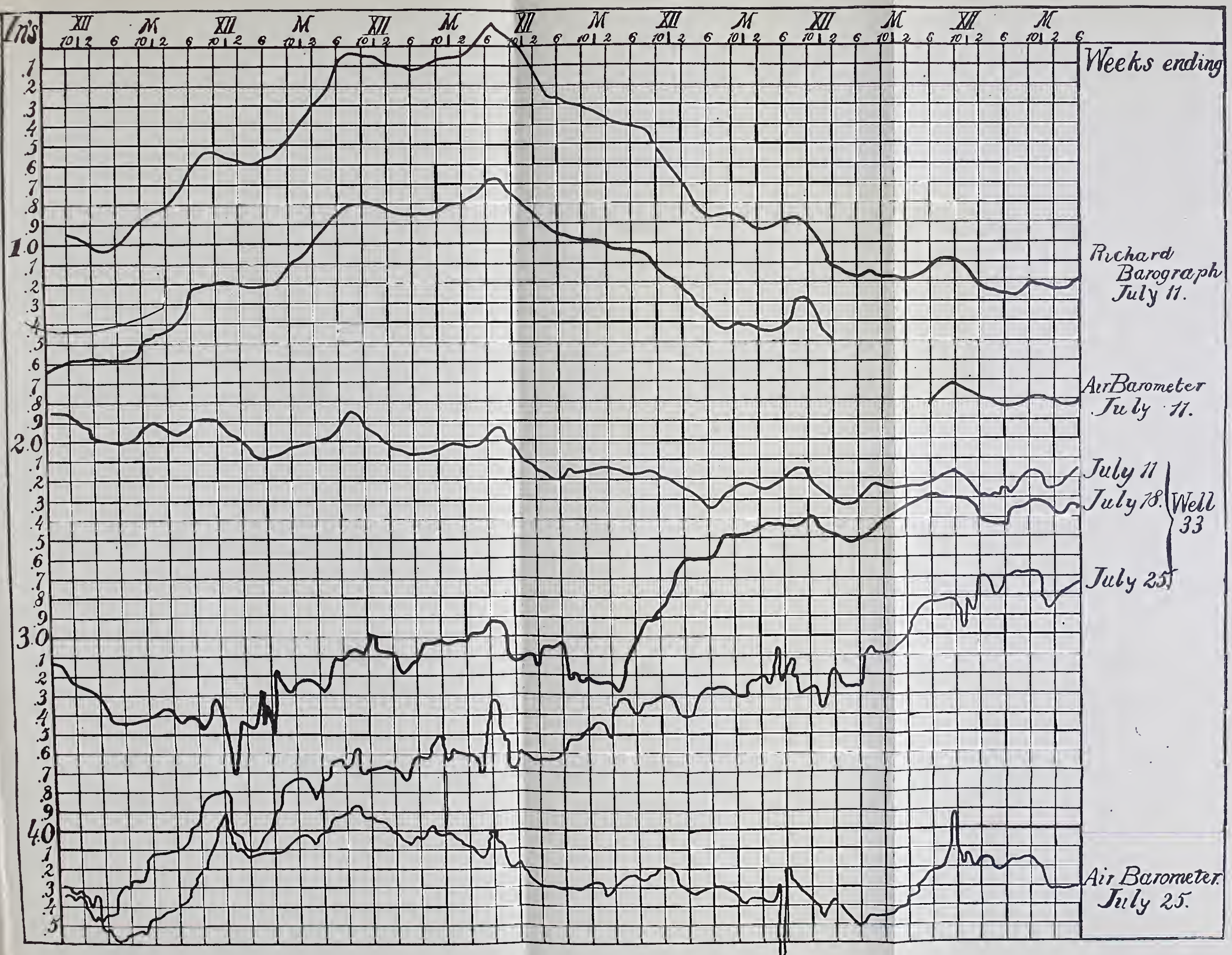

Plate VI. Semi-diurnal oscillations of the barometer and of water in wells.